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THE STUDY OF FOREST FIRE ATMOSPHERIC POLLUTION

(Reference USFS 4040 (4000))

UNIVERSITY OF WASHINGTON

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The Study of Forest Fire Atmospheric Pollution

ABSTRACT

This report contains experimental results of an investigation of the current practices of slash burning in relation to air pollution conducted under a grant from the U.S. Forest Service to the University of Washington.

The hypothesis was that incomplete combustion and greater emissions result from low temperature fires. Low temperature fires were associated with broadcast burns. Piled slash was expected to burn more completely and at higher temperatures, hence would produce less pollution. The results of field tests were compared with laboratory burns with respect to burning characteristics, gaseous and particulate emissions.

The more salient conclusions are:

1) Ground level particulate increased to nearly 10 times the background immediately downwind from the broadcast burn. The particulate in the smoke plume in the vicinity of the fire reduced visibility to 0.5 km, but at a distance of 19 km from the fire the visibility had increased to the level found over Seattle.

2) Similarly, high CO and CO_2 concentrations found at the fire site decreased rapidly to ambient conditions in horizontal and vertical directions.

3) Hydrocarbon analyses of gas samples revealed low concentrations of 25 components, the most significant of which appeared to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol, and ethanol. Several unsaturated components were found but the quantities were relatively low.

4) Results suggest that broadcast fires can be modeled in the laboratory with respect to burning characteristics, gaseous and particulate emission from different fuel density, packing, quality and method of ignition.

5) Air pollution aspects of slash burning can be minimized by establishing a high energy fire with a strong convection column under conditions favorable for rapid atmospheric dispersion. The fire should be of low residence time to consume the smaller fuels only.

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1. INTRODUCTION

In the Pacific Northwest, as in many other parts of the country, burning is the standard method of disposing of undesirable waste including logging debris and agricultural residue. About 200,000 acres (81,000 ha) of logging slash are burned annually west of the Cascades in the states of Washington and Oregon. In addition, 250,000 acres (101,000 ha) of grasslands are burned in Oregon.[1/] Many other forms of residue are also disposed of by burning.

Burning of waste contributes unknown quantities of gases and particulate to the atmosphere which may result in local or area wide pollution. In many cases burning appears to be the most practical and economical way of disposal. In the future it is hoped that more complete utilization will eliminate the necessity of burning. But until then, prescribed burning may be the only way to reduce fire hazard and thereby reduce the possibility of sustained pollution from wildfires occurring during periods of limited ventilation or low inversions.

Contribution of burning of agricultural wastes to air pollution have been studied in California by McElroy (1959), Bell and Waggoner (1961), Feldstein, et. al. (1963), and Darley et. al. (1966). Limited information has been available on the contribution of slash disposal to air pollution. In addition to this project, current research on the subject is being conducted at Oregon State University and Washington State University in cooperation with the Northern Forest Fire Laboratory at Missoula, Montana. The objectives of these studies are similar but the methods, fuels, and environmental conditions are quite different (Fritschen, 1967). This parallel research is justifiable because of the complexity of the problem and because techniques found optimum for minimizing pollution in one geographical region may not be universal.

Feldstein, et. al. (1963) state the general rule of thumb that the higher the combustion temperature and the longer the residence time at that temperature, the more complete the combustion will usually be if there is enough

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1/ Metric units are used in this report; see 10.2 for conversion factors.

oxygen present. They present data from single and multiple chamber incinerators which support the rule of thumb. However, local pollution is a function of incomplete combustion, total amount of material consumed and completeness of dispersion. Furthermore, the primary objective of slash burning is not complete consumption, but to 1) expose mineral soil for regeneration, 2) reduce fire hazard and 3) reduce undesirable species. Since fire hazard, especially ignition potential, rate of spread, and initial buildup, is directly related to the amount and percentage of fine fuel present, the objectives of slash disposal and minimum pollution may be achieved by a hot fire of sufficient duration to consume the fine fuels and favorable conditions for atmospheric dispersion. The hot fire, under field conditions, will provide the additional bouyant lift needed for dispersion.

2. OBJECTIVES

The primary objective of this project was to investigate the current practice of slash burning in relation to air pollution. Two avenues of approach were undertaken, the experimental and the descriptive. The experimental approach will be discussed in this report, and the descriptive will be presented in the final report.

The experimental approach was divided into three parts, slash burns, pile burns and laboratory burns.

The hypothesis tested was that incomplete combustion and consequently greater emissions result from low temperature fires. Low fire temperatures are usually associated with broadcast burns because of relatively low discontinuous available fuel loading, slow ignition techniques with a slow buildup of fire intensity: a "safe" fire is an implicit management objective. Conversely, piled slash, with higher available fuel loading and arranged so that oxygen was not limiting, could be expected to burn more completely and at higher temperatures, hence would produce less pollution.

The results of the field tests were to be compared with laboratory burns with respect to burning characteristics, gaseous and particulate emissions to determine whether the salient features of field test can be modeled.

3. EXPERIMENTAL METHODS

3.1. Experimental Sites

Most of the research experiments of this project were carried out at the Charles Lathrop Pack Experimental Forest of the University of Washington. This area is located at the southern boundary of Pierce County, Washington, 35 km south of Puyallup, 45 km southeast of Tacoma, 48 km southeast of Olympia (Fig. 1). The broadcast burn 2.1.2.[1/] and the pile burn 3.1.3. were conducted on a portion of Pack Forest near the confluence of the Mashel and Nisqually rivers about one mile downstream (north) from the mouth of a 152 m deep canyon (Fig. 2). The area selected for the burn is situated on an alluvial terrace at an elevation of 229 m, 76 m above the river. The land slopes gently to the northwest. To the south and east are deeply dissected foothills of Mount Rainier. To the north and west the topography is more gently dissected outwash and ground moraine deposited during the Vashon Ice Age. Vegetation in the area regenerated naturally following a forest fire in the 1920's, and consists of Douglas-fir with bracken fern, salal, trailing blackberry, hopclover, geranium, and other herbs and short shrubs.

3.1.1. Broadcast burn

Twelve hectares of Douglas-fir and associated species were clearcut during the spring and summer of 1967 (Fig. 2). The south 7.45 ha (18 acres) of the 12.1 ha (30 acres) area was burned in a broadcast burn. The area was centerfired with an electrical ignition system (See 3.3.1.).

3.1.2. Pile burns

Two cone-shaped piles, each 6 m in diameter at the base and 3 m and 6 m in height respectively were prepared from approximately .81 ha (two acres) of slash on the northern portion of the 12.1 ha clearcut. These piles consisted mainly of larger material, i.e., material greater than 2 cm in diameter.

3.1.3. Canadian fire

The Canadian Department of Forestry and Rural Development under the leadership of Bob Henderson, Fire Research Officer, Victoria Laboratory, Victoria, B.C. was conducting research on prescribed burns in an area north

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1/ 2.1.2. Indicates chapter 2, section 1, subsection 2.

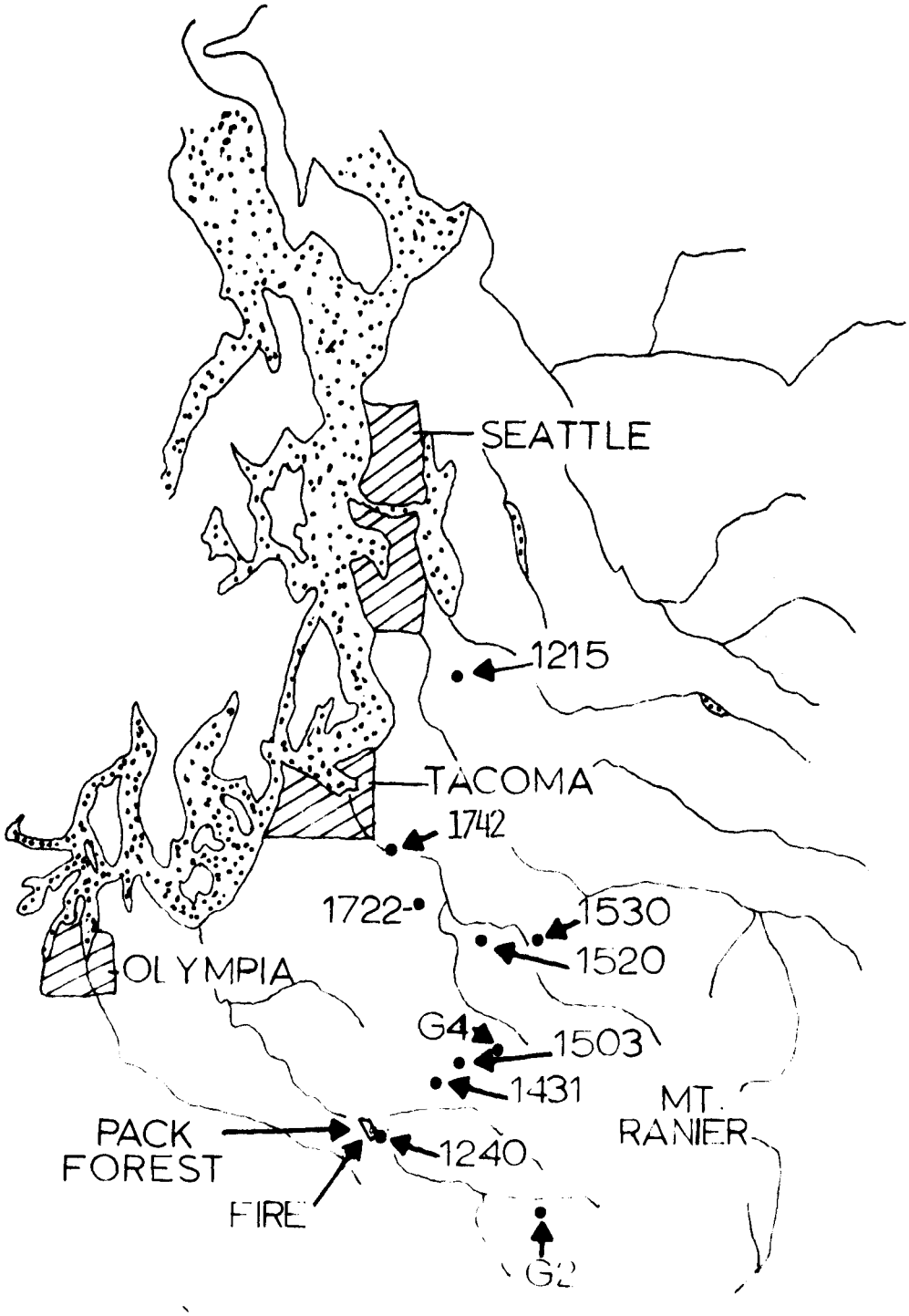


Fig. 1 Pack Forest and neighboring urban centers. Times (i.e., 1215) indicate location of aerial soundings 4.1.6.1. and G2 and G4 indicate gas sample locations 4.1.6.2.

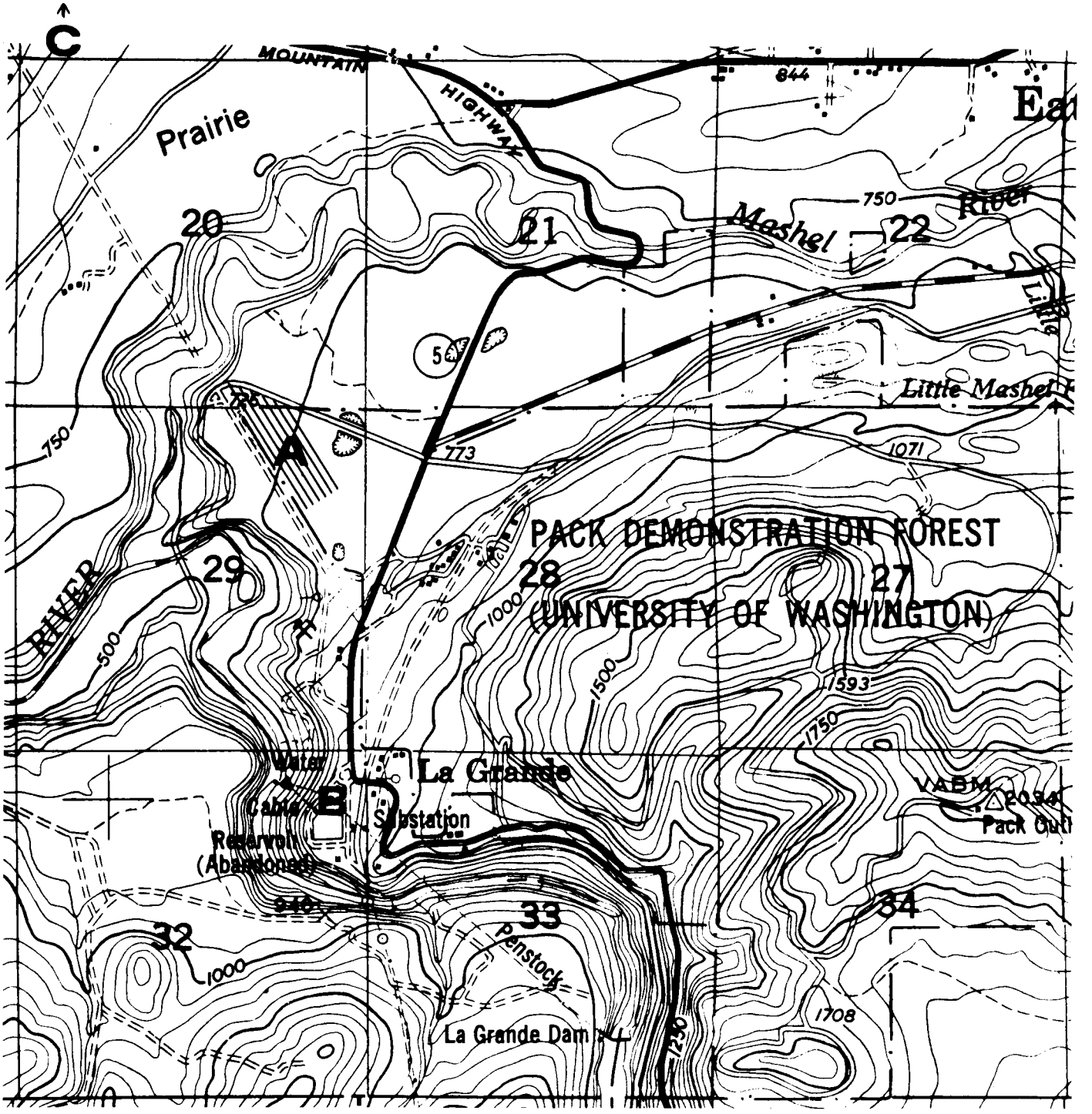


Fig. 2 Topography of Pack Forest area. The experimental site is at A and the remote camera sites are at B and C.

of Mission City, British Columbia. Several attempts were made to monitor the smoke from these prescribed burns. However, the unseasonably wet weather and logistics problems prevented monitoring of more than one fire. The particular fire monitored did not burn as planned and the data obtained are not worth inclusion in this report.

3.1.4. Laboratory Fire

Samples of Douglas-fir, western hemlock and western redcedar slash collected from the Pack Forest area were sent to Dr. Ellis Darley[1/] for laboratory analysis of combustion products. The results of these laboratory burns were compared with the results obtained under field conditions to determine the necessity for further field studies of pollutant emissions from slash fires. The system utilized for combustion and analysis is described by Darley, et. al., 1966.

3.2. Fuel Survey

3.2.1. Fuel weight

The quantity of fuel on the 7.45 ha (18.44 acres) used for the broadcast burn was estimated with a line intersect method similar to that utilized by Beaufait.[2/] The eighty-nine sample plots were established and measured during the summer of 1967. Postponement of the experiment to the summer of 1968 necessitated resurvey of the original plots prior to the burn. Material remaining on the ground after the burn was estimated using the same plots.

Sample points were established in a grid on 30 m centers using one meter concrete reinforcing rods driven vertically into the ground. Vertical transects were established at each sample point by locating a horizontal meter stick mounted on top of a staff compass at the reinforcing rod point. The direction of the meter stick was chosen as follows: six azimuths from 0 to 180° at 30° increments were assigned to the face of a die. The die was spun at each sample point and the meter stick aligned to the corresponding azimuth with the compass. The ends of the vertical transect were located by dropping a plumb bob from the ends of the meter stick.

1/ Dr. Ellis Darley, Statewide Air Pollution Research Center, Riverside, Calif.

2/ Personal communication. Dr. William Beaufait, Northern Forest Fire Laboratory, Missoula, Montana.

The total depth of slash was measured to the nearest centimeter at the ends and the middle of the meter stick. Exposure of mineral soil along the length of the transect line was visually estimated as percent of the line. Each piece of slash which intersected the transect was identified for species and classed as slash, brush or duff. Each piece was counted into one of three size classes, 0 to 1 cm, 1 to 10 cm and greater than 10 cm. The diameter of each log over 10 cm was measured to the nearest cm. Duff consisting of dried or decaying needles and twigs was measured to the nearest centimeter at each of three positions, ground level, mid-height and the top of the slash. The diameter of each piece of slash less than 1 cm was recorded on each of 10 one-meter transects. The diameter of each of these from 1 to 10 cm was recorded on four transects. These measurements were used to compute the average cross-sectional areas for these two size classes as shown in Table 1. Samples of the various brush species were checked throughout the burned area. The average cross-sectional area is estimated at 0.071 $cm.^2$ The number of pieces of 0 to 1 cm and 1 to 10 cm material in all transects was multiplied by the average cross-sectional area of these diameter classes, thus estimating the total area in each class. The area of material greater than 10 cm in diameter was computed from the plot data. Depth of duff was averaged for all plots. These figures were used to compute the volume of fuel on the one meter squared area bisected by each transect.

$$V = 100\ C(\pi/2L)$$

where V is the fuel volume in $cm^3 m^{-2}$, C is the total cross-sectional area of the material in cm^2, L is the total length of the transect in cm and $\pi/2$ is the eliptical correction for slash which cross the transect plane at other than right angles (Van Wagner, 1968).

The resulting averages were used to compute the total fuel volume and weight on the 7.45 ha as shown in Table 2.

The bulk density of the duff taken from the burn area was found to be 0.04 g cc^{-1}. The slash material was assigned a density of 0.40 g cc^{-1}, based on the values for oven-dried Douglas-fir as given by USFPL Wood Handbook (1955).

The amount of material remaining after the June 25 fire was estimated on 22 plots using the same sampling methods. Exposure of mineral soil was estimated on 45 plots as percent of transect length. Brush was unrecognizable

TABLE 1. Calculation of average cross-sectional area for material in 0-1 cm and 1-10 cm diameter classes, June 25 broadcast fire, Pack Forest, 1968

0-1 cm Diameter	No. of Pieces	Total Area	1-10 cm Diameter	No. of Pieces	Total Area
cm		cm^2	cm		cm^2
0.1	186	111.4601	1	44	34.5400
0.2	653	20.5042	2	10	31.4000
0.3	265	18.7222	3	1	7.0650
0.4	130	16.3280	4	2	25.1200
0.5	63	12.3637	5	4	78.5000
0.6	28	7.9128	6	0	
0.7	21	8.0776	7	0	
0.8	16	8.0384	8	0	
0.9	15	9.5377	9	0	
			10		
	1377	102.9448		61	176.6250
$c = \frac{102.9448}{1377} = 0.0748\ cm^2$			$c = \frac{176.625}{61} = 2.8955\ cm^2$		

TABLE 2. Weight and volume of fuels on the ground prior to June 25 broadcast burn, Pack Forest, 1968.

Material	No. of Pieces	Total Area	Volume per Plot	Wt. per Plot	Wt. for 7.45 ha. burn	
		cm^2	cm^3	g	Metric Tons	Short Tons
Duff	(5.53)		55300	2212	164.79	162
0-1 cm	15435	1154	2038	815	60.72	59.7
1-10 cm	653	1890	3337	1335	99.46	97.9
10 cm	34	6330	11147	4459	332.20	326.9
Brush	1559	110	194	78	5.81	5.7

as such and was included with the slash material. Density was assumed to be the same. Fuel in the 0 to 1 cm size class was almost completely consumed by the fire. The average cross-sectional area was assumed to be 0.5 cm^2 The average cross-sectional area in the 1 to 10 cm size class was found to be 23.9 cm^2 on the basis of 24 measurements. The results are shown in Table 3.

3.2.2. Fuel moisture content

Samples of each type and diameter class of slash were collected from each sample point the day previous to the fire. This was because firing grenades were placed in the slash area the morning of the burn. Weather conditions affecting fine fuel moisture were comparable on both days. (See section 4.1.1.) These samples were stored in polyethylene bags at -5°C until moisture content determinations could be run.

Moisture content determinations were to be made with a Carl Fisher aparatus; however, no satisfactory technique for handling milligram subsamples was found which would allow for the large intra-sample variations in these samples. Consequently moisture content determinations were made on a pilot basis using weight loss after drying at 105°C, weight loss after vacuum oven drying, and toluene distillation. After the initial pilot runs, the vacuum oven technique was chosen as the best compromise between repetition and analysis time.

3.3. Ignition Techniques

3.3.1. Broadcast fire

Since engineers participating in the study of the clearcut block burn were studying energy exchange, a fire quickly ignited with a high rate of energy release was desired. This was because one dominant convection column with basal air entrainment was required. A secondary factor affecting the ignition strategy was the large amount of green fuel present on the block because of the one year "layover" of slash. Green bracken fern, salal, trailing blackberry, hopclover, geranium and other herbs and short shrubs made up a nearly complete green ground cover 25 to 60 cm tall. Considerable heat output would be necessary to overcome the high fuel moisture of this live fuel element.

An electrical ignition system with an areally-distributed fuel booster was used to obtain the quick hot fire. This type of ignition and burning strategy is occasionally used on better planned prescribed burns in the forests of central and northern California and the Pacific Northwest (Reifsnyder, 1956; USFS unpub., 1966; Schimke and Dougherty, 1966). Because the fuel was sparse and discontinuous on the northwest one-third of the block, it was decided by the experimental team to confine the burn to the southeasterly 7.4 ha.

TABLE 3. Weight and volume of fuels remaining after June 25 broadcast burn, Pack Forest, 1968.

Material	No. of Pieces	Total Area per Plot	Volume per Plot	Wt. per Plot	Wt. for 7.45 ha. burn	
		cm^2	cm^3	g	Metric Tons	Short Tons
Duff	(2.71 cm)		27100	1084	80.76	79.5
0-1 cm	41	20.5	58	23	1.71	1.7
1-10 cm	39	932.1	2662	1065	79.34	78.1
10 cm	23	4614	13345	5338	397.68	391.4

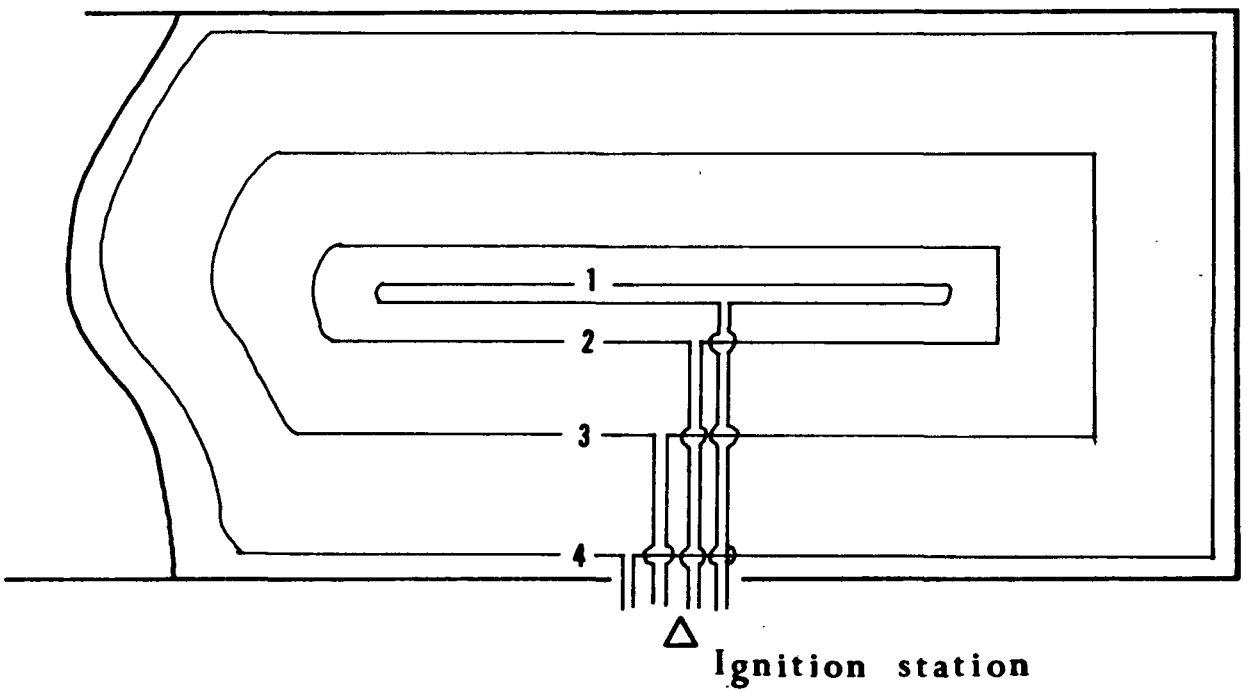


Fig. 3 Electrical ignition plan of the broadcast fire on Pack Forest, June 25, 1968. Circuits 1, 2, 3, and 4, as shown, were fired in that order.

Four hundred and twenty ignition points were systematically located over the slash area. One central line of ignition points extended down the middle of the rectangular burning unit, Fig. 3. Three rings of ignition points were also located, the innermost ring was 15 m from the center line. The middle ring was 45 m from the center line. The outside ring was 83 m from the center line or 7.5 m from the outside edge. The outer two rings were split into two separate circuits because of high accumulated resistance.

The circuits were wired in series because voltage force can be calculated more readily and because less wire is necessary (than parallel) thus reducing the cost. An ohmmeter was used for constant field checks of resistance and continuity of circuits. A total of 5,486 m of aluminum wire was used for the electrical circuits. Aluminum wire was used because it would melt at temperatures expected during the slash burn, and it would not have to be retrieved after the burn to prevent injury to test personnel or wildlife. A jellied fuel, identical to napalm, was used as the fuel booster package at each ignition point.

The central ignition line and the northwesterly end of the block were fired with 1.06 l grenades. Greater heat output was judged necessary at this northwesterly location because of the large amounts of green fern, herbs and brush with high live fuel moisture. Plastic packages filled with the fuel booster, called "blivets," 0.78 l in volume, were used for all of the remaining ignition points. The thickened napalm was used because preliminary tests showed it to have the following advantages:

1. Easy to ignite.
2. Sustained, hot flame: 7×10^6 cal (28,000 BTU) heat content per 453 g (pound) and an approximate burning temperature of 770°C (1400°F). Other fuel boosters in use (i.e., petroleum gels) have a heat value of approximately 4.5×10^6 cal (18,000 BTU) per 453 g (pound) and burning temperatures of 440°C (800°F), (Schimke and Dougherty, 1960). The napalm fuel booster units burn longer (6-10 minutes) than any other incendiary device used in forest fire operations, (Dell and Ward, 1967).
3. The fuel will not flash off.
4. Manufacturers claim the fuel residue is not injurious to human or animal life.

A total of 249 kg of the jellied fuel was used. Black powder squibs and spitter fuses were the ignition source. A 50-cap condensor-type blasting machine was used as the power source.

The central circuit was ignited first. Then each ring or half ring was ignited two minutes apart with the peripheral ring ignited last. The firing strategy was planned to produce the central convection column and basal air entrainment required for the study.

3.3.2. Pile fires

The piles were ignited around the base with standard drip torches using a 3:1 mixture of diesel fuel and gasoline.

3.4. Emission Analysis

3.4.1. Suspended particulate matter

3.4.1.1. Ground sampling Particulate emissions were monitored continuously by means of high volume air samplers located near the downwind perimeter of the fire. Suspended particulate matter was collected on glass fiber high volume filter mats (MSA No. CT-75428).

The particulates from the high volume filters were extracted with benzene in a Soxhlet extractor. The extract was analyzed by a gas chromatograph -- mass spectrometer combination employing a 50 ft. SE 30 column.

3.4.1.2. Airborne Sampling Particulate in the smoke plume was determined as the light scattering coefficient measured with an airborne version of the continuous integrating nephelometer developed under this grant (Ahlquist and Charlson, 1968). The light scattering coefficient and air temperature were measured and recorded simultaneously by means of a special digitizing circuit and a four-track portable tape recorder. Air pressure (altitude) was recorded on the third track and the fourth track was used for voice recording of the observations.

The resulting magnetic tape data from each sounding was plotted directly with a Leeds and Northrup XY plotter. These results were converted to micrograms per cubic meter following the method of Charlson, et. al. (1968), and plotted with potential temperature versus altitude.

3.4.2. Carbon monoxide and carbon dioxide

3.4.2.1. Broadcast fire

3.4.2.1.1. Ground sampling The air samples were taken at two locations with respect to the fire. Flame gas samples were taken from the immediate vicinity of the flames. Smoke samples were taken at ground level near the downwind perimeter of the fire.

Two special sampling techniques were developed for this project, one for sampling flame gases and the other for sampling smoke on the ground without the benefit of electrical power.

Samples of flame gases from within the actual fire were obtained by a technician wearing an asbestos suit. The samples were collected in an evacuated 1,000 ml boiling flask fitted with a 90-degree connecting tube and a stopcock with a tapered ground glass joint (Kimax 45000). These flasks were supported on a metal probe which also carried a thermocouple for measurement of the flame temperature.

The distribution of the gases downwind from the fire was mapped using the water displacement air sampler developed for this project, see section 10.3. This sampler was used primarily to determine the carbon monoxide and carbon dioxide concentrations. However, hydrocarbon gases were identified and measured from the samples taken with this device during the broadcast fire on June 25. These samplers were changed periodically during the course of each fire giving a time-sequence of gaseous emissions throughout the fire. Since these samplers could be adjusted for a sampling period ranging from six minutes to two hours, this system provided an automatic integration over the sample period. These samplers were located as shown in Fig. 4 for the June 25 broadcast fire.

Grab samples of smoke were obtained from both the fire perimeter and from the instrumented aircraft within the plume. These samples were collected using evacuated breathing oxygen tanks and a mylar bag which was filled by means of a rubber squeeze bulb (Breysee and Bovee, 1966).

Spot analyses of carbon monoxide concentrations were made using Monoxor Chemical Detector tubes. The concentration of hydrocarbon gases was also spot checked using a Johnson-Williams Combustible Gas Detector, Model SSP.

The concentrations of carbon monoxide and carbon dioxide were measured in the water displacement air samplers by means of Beckman non-dispersive infrared gas analyzers operated in series. The analytical train is shown in Fig. 5. Water vapor and particulates were removed by a Dryerite tube and a 41 mm glass mat in-line filter. The dried and filtered sample was analyzed for carbon monoxide concentrations on a Beckman 315, 0 to 100 ppm, long path carbon monoxide analyzer. The outlet of this analyzer was connected directly to the inlet of the Beckman 215A, 0 to 600 ppm, short path differential carbon dioxide analyzer using dry nitrogen in the reference cell. Flow rates through

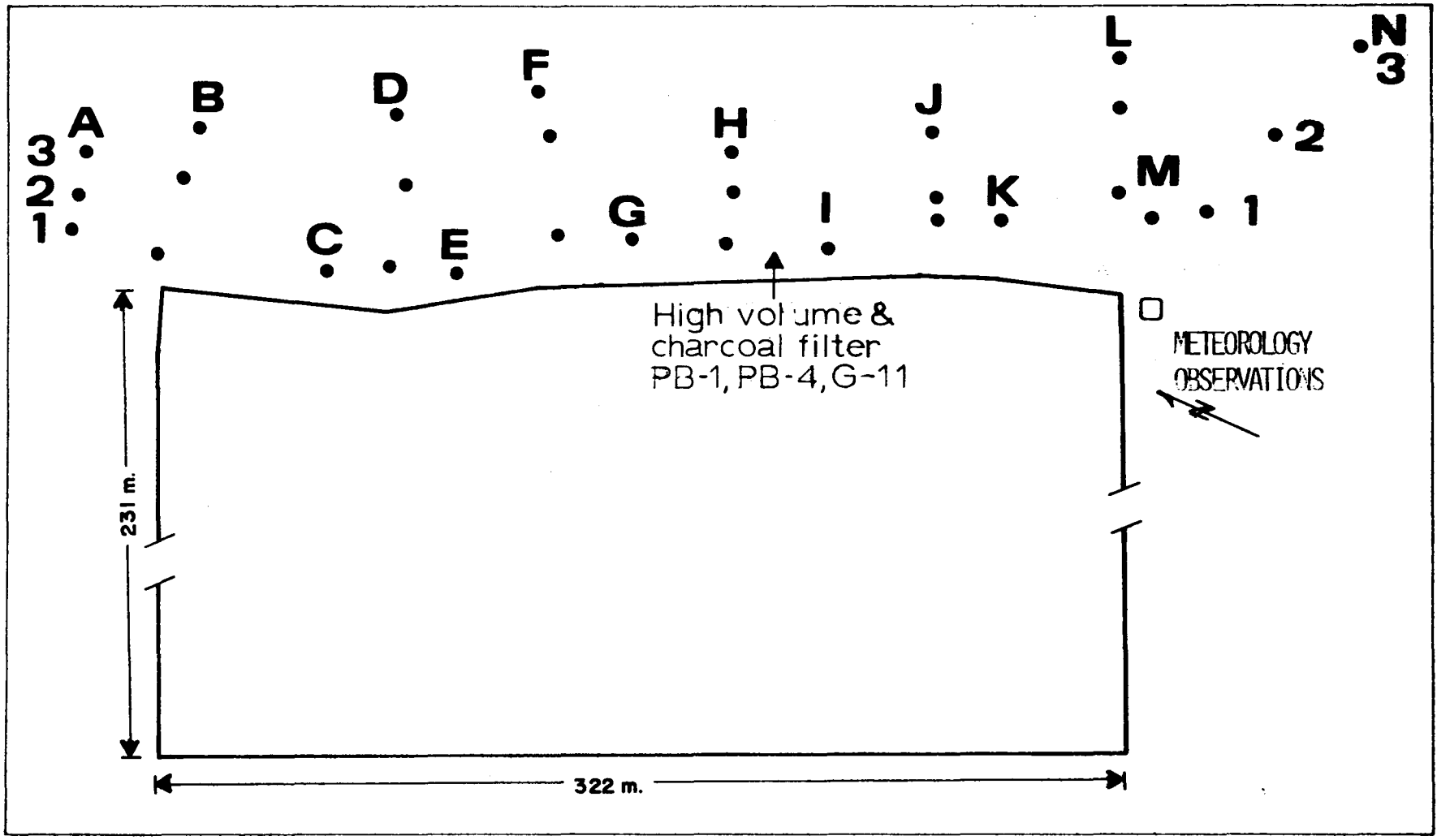


Fig. 4 Location of water-displacement air samplers, other samplers and meteorological observations for June broadcast fire, Pack Forest, 1968.

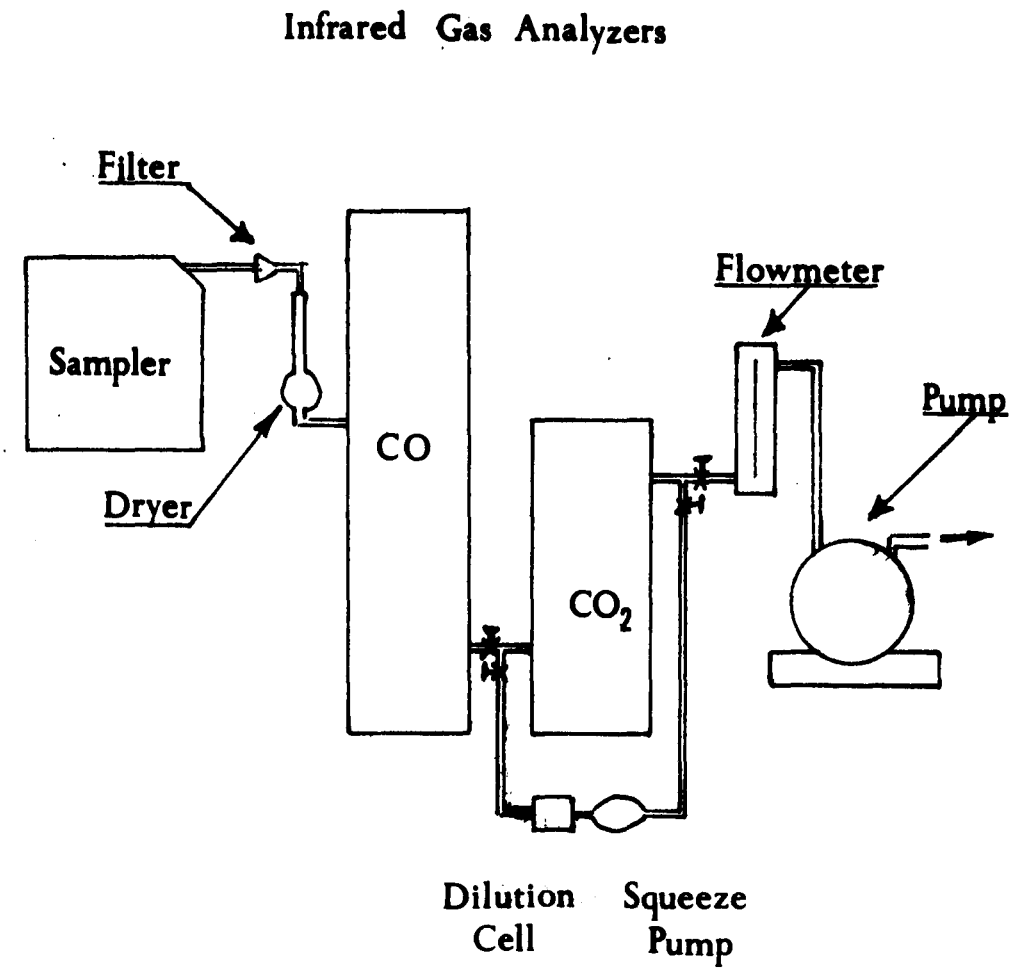


Figure 5. Analytical train for CO and CO_2 analysis.

the system were maintained at 50 ml per minute by varying the inlet control of the vacuum pump.

Gas samples were diluted when the carbon dioxide concentration exceeded 600 ppm. The dilution apparatus consisted of a 50 mm length of 76 mm tubing connected in series with a rubber squeeze bulb pump. The sample was shunted from the carbon monoxide analyzer through the dilution train and when full the train was closed. The carbon dioxide analyzer was then flushed with dry nitrogen and the dilution system containing the sample was reconnected to both the inlet and the outlet of the analyzer. The nitrogen in the sample cell was mixed with the sample air by means of a squeeze pump. An accurate dilution factor was obtained by calibrating the dilution system with 370 ppm carbon dioxide in air. This dilution factor was applied to the measured concentration to give the original concentration of carbon dioxide in the system.

The samples taken from within the fire were analyzed with the same system. A much higher concentration of carbon monoxide and carbon dioxide required a dilution factor of 83.331 which was obtained by replacing the 76 mm tubing in the dilution train with a 19 l carbuoy and operating the dilution system in a closed path circuit through both analyzers. The dilution system was calibrated with dry nitrogen containing 250 ppm carbon monoxide and compressed air containing 370 ppm carbon dioxide.

The contents of the sample flask were at less than atmospheric pressure due to the difference between the collection and analysis temperatures. Each flask was brought to ambient pressure by the addition of dry nitrogen. The concentration of the diluted gas was measured with the analytical train and the true concentration of the original gas then was calculated from the known flame temperature. By assuming that the pressure change within the sampler was due entirely to the difference in temperatures, the correction equation simplified to:

$$Xt = \frac{(T_1)}{(T_2)} X_o$$

Where Xt is a true concentration, X_o the measured concentration, T_2 is the gas temperature at time of analysis in degrees Kelvin and T_1 is the flame temperature when sampled in degrees Kelvin.

3.4.2.1.2. Airborne Sampling. Smoke samples were taken within the plume by personnel in the instrumented aircraft. These samples were analyzed for CO and CO_2 with a Beckman IR-2 infrared spectrophotometer fitted with a 10 m gas cell.

3.4.2.2. Pile fire Smoke samples from the plume of the instrumented pile fire burned on July 11 were obtained by suspending the water displacement air samplers in the plume about 12 m above the ground. Lines thrown across the tight wire were used to raise and lower the air samplers as shown in Fig. 6. The gas samplers were analyzed as described in section 3.4.2.1.1.

3.4.3. Hydrocarbon gases

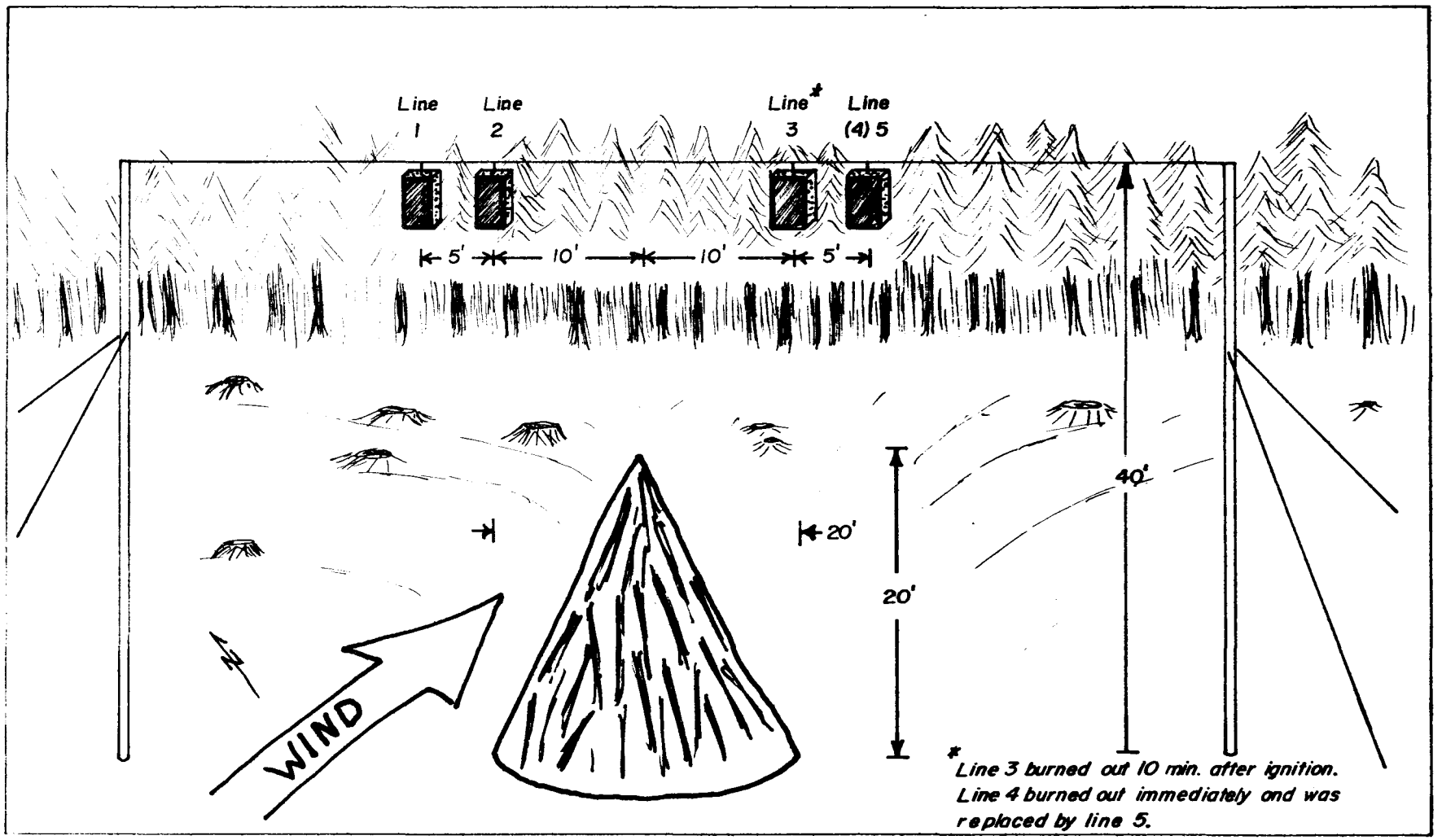
3.4.3.1. Broadcast fire. Contaminants in several of the air samples were concentrated by freezeout at liquid nitrogen temperatures and analyzed by a combined gas chromatography - mass spectrometry technique (Bovee, et. al., 1966). A Varian-Aerograph Model 1200 gas chromatograph was equipped with a 10-foot stainless steel Porapak Q column. Temperature was programmed from 40°C to 220°C and the range of analysis extended from ethylene to xylene, using the flame ionization detector. A splitter placed just ahead of the detector directed part of the column effluent to a Perkin-Elmer Hitachi RMU-6D mass spectrometer. A mass spectrum was recorded for each chromatograph peak plus additional spectra for compounds not detected by the flame ionization detector. Hydrocarbon gases were also monitored continuously throughout the broadcast fire on June 25. These gases were collected on a charcoal filter which was operated from 1330 to 1800. The material collected on the charcoal was desorbed under vacuum, collected in a liquid nitrogen freeze trap and analyzed by gas chromatography and mass spectrometry.

3.5. Photography

3.5.1. Broadcast Fire

Close up and distance photographs were taken to study the action of the flames and the intensity of the fire, and to study the buildup and smoke migration. For the closeup pictures, four 16-mm movie cameras were located at the four corners of the fire. The cameras were adjusted to take a frame every 10 seconds. They were mounted to view the fire at right angles from two sides, the north and the south.

The distant cameras were located 3.8 km to the north and 1.4 km to the south. These were 16-mm movie cameras adjusted to expose one frame every 10 seconds. In addition, another 16-mm movie camera was used to take pictures of the fire development from the instrumented aircraft. Continuous movies were obtained with this camera. 35 mm slides were taken sequentially of ignition and fire buildup, smoke characteristics and all test operations.



Location of water-displacement air samples for July 11 pile fire, [illegible] Forest, 1968.

3.5.2. Pile fire

The pile fires were photographed with two 16-mm movie cameras mounted to obtain pictures at right angles to each other. The cameras were operated continuously for short periods upon command using two-way radios. 35-mm slides of fire and smoke behavior and test operations were taken.

3.6. Meteorological observations

Instrumented towers were located on the southeast and the north-central portions of the broadcast area to monitor meteorological conditions during the fire. The northcentral tower carried an anemometer and wind vane, mounted at 13.7 m to indicate the upwind conditions, but was not functional during the fire. The southeast tower was 22.9 m tall. Psychronometers and anemometers were mounted at 1.5, 4.6, 9.1, 13.7, 18.3 and 22.9 m above the ground to monitor downwind conditions. A wind vane was mounted on top of the tower. The signals from these sensors were recorded at one minute intervals on an automatic data logging system. Due to the slope of the fire site, the base of the southeast tower was 3 m. below the fire level.

General meteorological conditions were also monitored at the ignition site, 4.1.1.

Because of the failure of the upwind tower, upwind and downwind comparisons are not available.

4. RESULTS AND DISCUSSION

4.1. Broadcast burn

4.1.1. Firing Techniques

Ignition was at 1338, June 25, 1968. Weather measured at the ignition station is shown in Table 4. Within 15 minutes a strong central draft formed

TABLE 4. Weather measurements* at ignition station, Pack Forest Broadcast burn, June 25, 1968.

Time	Cloud Cover	Temperature Wet	Temperature Dry	Relative Humidity	Wind Dir.	Wind Vel.
	Tenths	°C	°C	%		m sec^{-1}
1050	0.1	19.4	25.8	56	NNW	0.4-4.0
1210	0.1	20.0	27.8	48	NNW	0.4-2.6
1315	0.1	21.4	30.0	46	NNW	1.7-5.2 Gusts to 6.1
1430	0.1	21.6	30.0	46	NNW	1.7-4.3

*June 23 and 24 were sunny and warm. Seattle-Tacoma Airport reported 27°C the afternoon of June 24, 1968.

with all ground level smoke flowing into it (4.1.4.). The strong ground indraft was strengthened on the north and west sides by the NNW prevailing wind. The smoke plume pierced a fairly pronounced inversion (detected by research aircraft) extending from 640 m to 914 m over the fire (see Fig. 10). The smoke plume rose to approximately 1370 m and sheared in a south-southeast direction where it encountered the strong upper level inversion base, and drifted well away from the fire area.

By 1 1/2 hours after ignition only disorganized small sources of smoke remained. In the absence of the strong convection column this smoke drifted and diffused at low elevations. By 2 1/3 hours after ignition, little smoke was visible over the entire unit.

Fire control was not a problem. Although the fire was extremely turbulent, no spot fires occurred in the adjoining uncut stand. A primary reason for the lack of spot fires was the strong central convection column with the accompanying strong indraft at the edges of the burn: firebrands were transported upward in the convection column where burnout ultimately occurred.

The thickened or gelled napalm used as the fuel booster on the clearcut burn has the trade name "Burnol." The manufacturers could not supply the chemical composition of this specific product.

Analysis of the napalm fuel booster made in Fontana, California and at the University of Washington as part of this study are shown in Table 5.

TABLE 5. Chemical composition of the fuel booster "Burnol."

Compound	Percent		
Chevron Gasoline (low octane)			94
Activating compounds			6
Aluminized soap*		95	
Organic acids from cocoanut oil (extracted copra oil) tri myristin, tri laurin, tri palmitin, tri stearic	50		
Naphthalic Acid	25		
Oleic Acid	25		
Silica aerogell (devolatilized)		5	
Totals	100	100	100

*Traces of glycerides detected.

Calculated emissions from the fuel booster, assuming total combustion, are shown in Table 6. When compared with the results of Darley's laboratory tests of cellulose fuel

TABLE 6. Gaseous and elemental emission from the fuel booster used on the broadcast burn, June 25, 1968.

Component	C		H		O		CO		CO_2	
	kg	%	kg	%	kg	%	kg	%	kg	%
Gasoline	197	84	37	16						
Organic fatty acids	4.8	76	0.9	11	0.9	13				
Oleic acids	2.7	77	0.4	12	0.4	12				
Naphthalic acid	2.5	6.7	<0.4	4	1.1	30				
Subtotal[1/]	10.1		<1.8		2.5					
Total	208		>38		2.5					
All carbon converted to CO							461			
All carbon converted to CO_2									724	
C, CO, CO_2 produced in a 2:1:7 ratio	29.5	20					45.8	10	508	70

[1/] Total amounts of C, H and O in the minor components amounts to 6 percent of the total material in the fuel boosters.

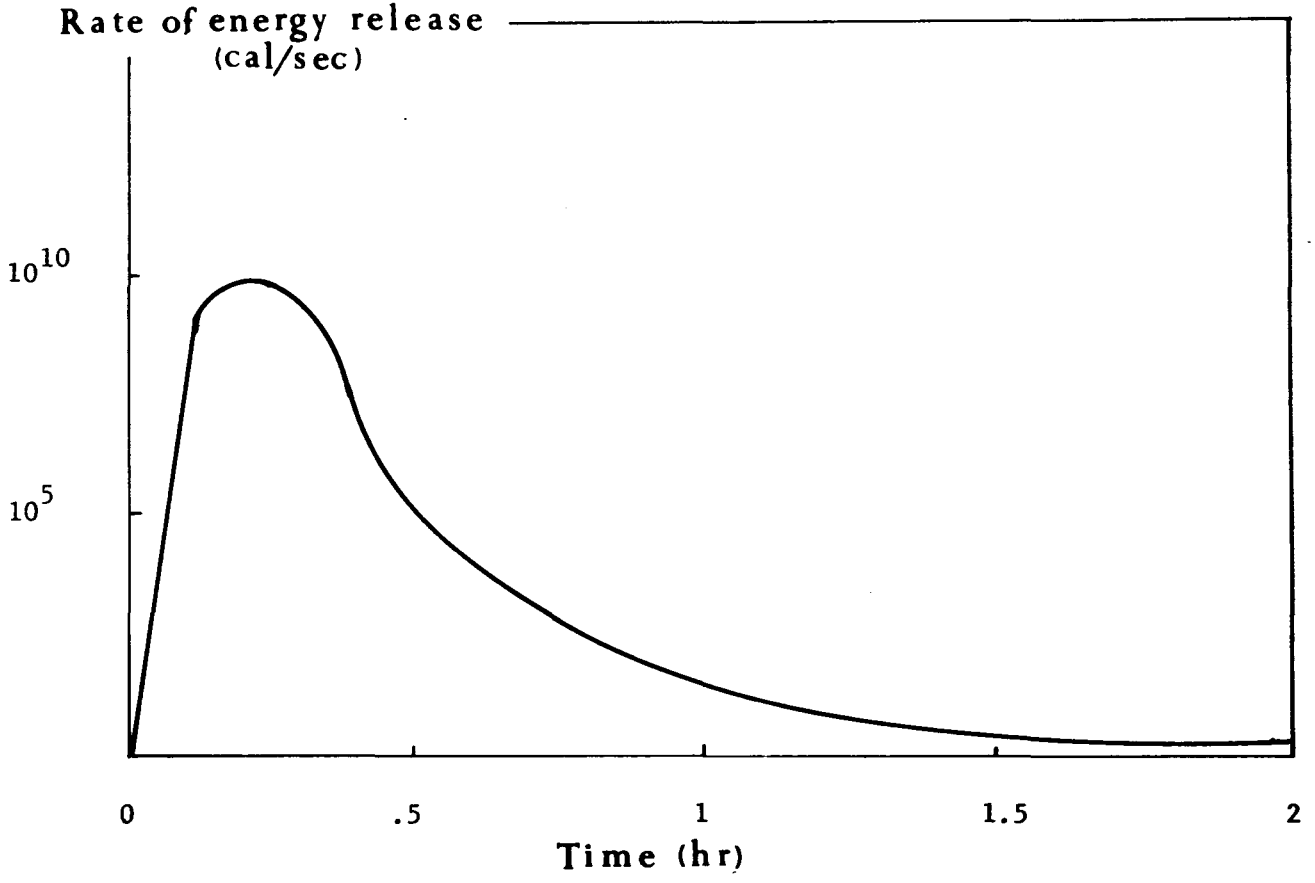


Fig. 7. Assumed rate of energy release for the broadcast fire on Pack Forest, June 25, 1968.

section 4.3.2, the fuel booster could account for 11 percent of total (wood fuel plus fuel booster) CO and 3 percent of total CO_2 emitted during the clearcut burn.[4/]. Each fuel booster package achieved burnout in 7 minutes according to averages obtained from burning tests of 12 packages. Total fuel booster burnout thus occurred 19 minutes after ignition. Total fuel booster emission was during this period.

However, during phase 1 (first hour of burning) CO and CO_2 concentration measured by the sampling net at the ground level were low (5 ppm and 500 ppm, respectively, Fig. 11).

Hydrocarbon gases during phase 1 appear to be saturated and would not contribute appreciably to photochemical smog (Table 17). These measurements are of emission from both fuel booster and woody fuel. Since the greatest plume rise occurred during this period, most emissions were carried well away from the fire area and were subject to rapid dilution. Visibility reduction was greatest during the early stages of the fire and the fuel booster was responsible for some portion of smoke volume and density.

Lowry (1967) has published a physical model which is useful for estimating requirements for rise of large smoke plumes from prescribed fires. He suggests that rates of energy release are too small on most slash fires to achieve good plume rise necessary for minimization of air pollution. His model gives a basis for estimating the rate at which fuel must be burned to achieve a given plume rise under stated atmospheric conditions. Lowry's model was used to evaluate rates-of-energy release on the broadcast burn. The following measurements and assumptions were used.

Atmospheric pressure	P	=	1.0 atmosphere
Gradient wind	u	=	2 m $sec.^{-1}$
Plume rise	H	=	1000 m
Radius of plume at height times radius of burn area	r(R)	=	200 m
Radius of plume times vertical wind speed	r^2W	=	2.0×10^5 m^3 $sec.^{-1}$
Dimension less bouyancy	B	=	.2
Rate of heat generation	L	=	6.8×10^{o}cal $sec.^{-1}$

4/ Fuel booster calculations assume total combustion and an estimated $C/CO/CO_2$ ration of 2:1:7 and are not adjusted for smoke and residue as are Darley's.

Thus in order to achieve a plume rise of approximately 1000 m, approximately 6.8×10^9 cal sec^{-1} heat release would be required.

Based on fuel consumption values of Table 10, the same heat of combustion figures used by Lowry, observations by fire scientists assigned to the experimental burn, and integration over 2 hours of primary combustion activity, the maximum rate of energy release on the experimental burn was approximately 12.8×10^9 cal sec^{-1}, Fig. 7. This average release rate was achieved approximately 7 minutes after ignition and was maintained, on the average, until approximately 20 minutes after ignition. The plume rose to about 1370 m in spite of the inversion, and, based on theoretical calculations, would have risen to about 1830 m had the plume not encountered the upper level inversion (Fig. 10).

This plume rise would not have been achieved using conventional slash burning techniques, i.e., low temperature ignition devices, slow firing, slow and discontinuous fire development and long burnout times. Although impossible to prove quantitatively from the data obtained during this study, it is doubtful if the smoke plume could have risen higher than the base of the low level inversion, 600 m.

Direct costs of burning the 7.45 ha. (18.44 acres) unit were $116 per ha ($47 per acre, Table 7). These costs included the fuel booster, the

TABLE 7. Direct burning costs, using fuel boosters and electrical ignition for the 7.45 ha broadcast burn.

Item	Cost
Fuel booster	$ 371.76
Ignition Squibs	118.50
Spitter fuse	6.00
Aluminum wire	72.20
	$ 568.46
Manhours	
Wire layout - 6 man days Prepare booster packages - 2 man days Standby crew (20 men)	$ 287.30
TOTAL COST	$ 855.76

complete ignition system, manhours for installation, and fire control crews. An adjoining 4.7 ha (12 acre) unit was burned with conventional drip torches and diesel fuel. An attempt was made to obtain the same rapid rate of heat generation as on the 7.45 ha unit. The cost of burning the smaller unit was $133 per ha ($54 per acre). However, because the risk of wildfire was high, a 30-man standby fire control crew was used.

4.1.2. Fuel burned

The pre- and post-fire inventories, 2.2.1., were used to compute the total amount of fuel burned. The results are shown in Table 8. The weight

TABLE 8. Weight changes on 7.45 ha (18.44 acre) broadcast burn, June 25, 1968.

Material	Total Weight Change		Change Per hectare	Change Per acre
	Short ton	Metric ton	Metric ton	Short ton
Duff	-82.5	-84	-11.3	-4.47
0-1 cm (includes brush)	-63.7	-64	- 8.6	-3.45
1-10 cm	-19.8	-20	- 2.7	-1.07
< 10 cm (1 cm. shell)	-90.3	-92	-12.3	-4.90
TOTAL	-256.3	-260	-34.9	-13.90

change for duff may be greater than shown. In post-burn samples no distinction was made in most cases between burned duff, unburned duff, and ashes. The weight of material greater than 10 cm in diameter increased after burning. This may have been due to the low sampling intensity, or the bias introduced either by burial of this material by fine fuels before the fire or exposure of the material afterwards. However, only an outer shell of approximately 1 cm was charred on material 10 cm in diameter or larger. Since the amounts of material in this size class was approximately the same in both surveys, an estimate of the material which actually burned was made by computing the volume per plot of this 1-cm shell and using this figure in Table 8.

The estimated percent of mineral soil exposed prior to the burn was 10 percent. The estimated percent of mineral soil exposed after the burn was 18 percent. This difference may not be statistically significant since only half of the plots were remeasured after the burn. The average duff depth prior to and after the fire changed from 5.53 cm to 2.71 cm Some of the material represented as duff in the post-fire remeasurement consisted only of ashes, and some

was partially burned. No measurements were made to determine relative proportions of ashes, burned duff and unburned duff. However, reports by cooperating fuels scientists indicated total reduction in duff load on the area was light considering the intensity of the fire (Fahnestock, Morris, 1968).

4.1.3. Fuel moisture

Moisture content for each strata of the slash material was averaged for all plots. The results are shown in Table 9.

TABLE 9. Moisture content (expressed as percent oven-dry weight) of fuel on sample plots prior to June 25, 1968 broadcast burn, Pack Forest.

Material	Moisture Content	Standard Deviation	Range
	percent	percent	percent
Brush	190	136	7-622
Duff, ground	48	22	18-120
Duff, mid-transect	28	30	5-141
Duff, top	19	15	4-34
0-1 cm, ground	21	31	2-165
0-1 cm, mid-transect	25	48	7-282
0-1 cm, top	17	12	2-78
1-10 cm, ground	22	7	11-49
mid	19	8	2-45
top	23	7	10-39

4.1.4. Photography

On the basis of time-lapse photography, the June 25 fire was broken down into three stages each with characteristic fire and plume behavior. The first stage was characterized by fire buildup, a hot fire, convergence and eddy mixing in the resulting convection column. This stage lasted until 1410 (section 4.1.5.), and was roughly equivalent to the period I gas samples, section 4.1.6.2.

Stage II, corresponding to period II gas samples, 4.1.6.2., was characterized by a general dying down of the fire, a tendency for the convection column to lay over at the ground, but with abundant fire remaining in the area. The stage II fire gradually diminished until by 1510 only scattered hotspots, i.e., campfire size blazes, remained in the area. This

was termed stage III although it had very indefinite beginnings. The period III gas samples were taken predominantly after the fire had reached this stage. So little fire remained in the area that most experiments other than gas sampling were terminated.

4.1.5. Meteorological conditions

General meteorological conditions at the ignition site were given in section 4.1.1. Meteorological conditions at the southwest corner of the broadcast burn are shown in Figs. 8 and 9. The prevailing wind was from the northwest at about 3 m sec^{-1}. However, during phase I, the buildup period, air flowed into the fire from all directions. This is illustrated in Fig. 8, between 1340 and 1410. The shaded area of wind directions indicates the period of air flow into the fire. During this period, the wind speed decreased from ambient as the air started to converge. Wind speed increased as convergence reached a maximum, 1510, then decreased as the fire started to lose energy. During phase II of the fire, the wind direction switched around to the northwest again and the velocity increased to the original level.

Air temperature substantiates the above statements (Fig. 9). The inexact correlation between wind direction and low air temperatures is due to the difference in time response of the wind vane (instantaneous) and the temperatures (about two minutes). During the buildup, the temperature dropped as fresh air moved into the fire (Fig. 9, 1340 to 1410). Air temperature increased again as the wind direction changed to the northwest causing the heated air from the fire to reach the temperature sensors. The fire energy system very obviously dominated the mesoscale weather at the burning site during the 1340-1410 period.

4.1.6. Emission Analysis

4.1.6.1. Suspended Particulate Matter Gas chromatographic analysis of the benzene extracts from the high-volume filter mats showed up to 50 distinguishable peaks. Mass spectral data obtained simultaneously indicated the presence of alkanes, alkenes, alcohols, ketones, and essential oils.

The particulate loading and extractable percentage before and during the burning is shown in Table 10. The background particulate loading was high for a rural area and probably due to slash burning on the previous day. The particulate loading increased the morning of June 25, prior to ignition.

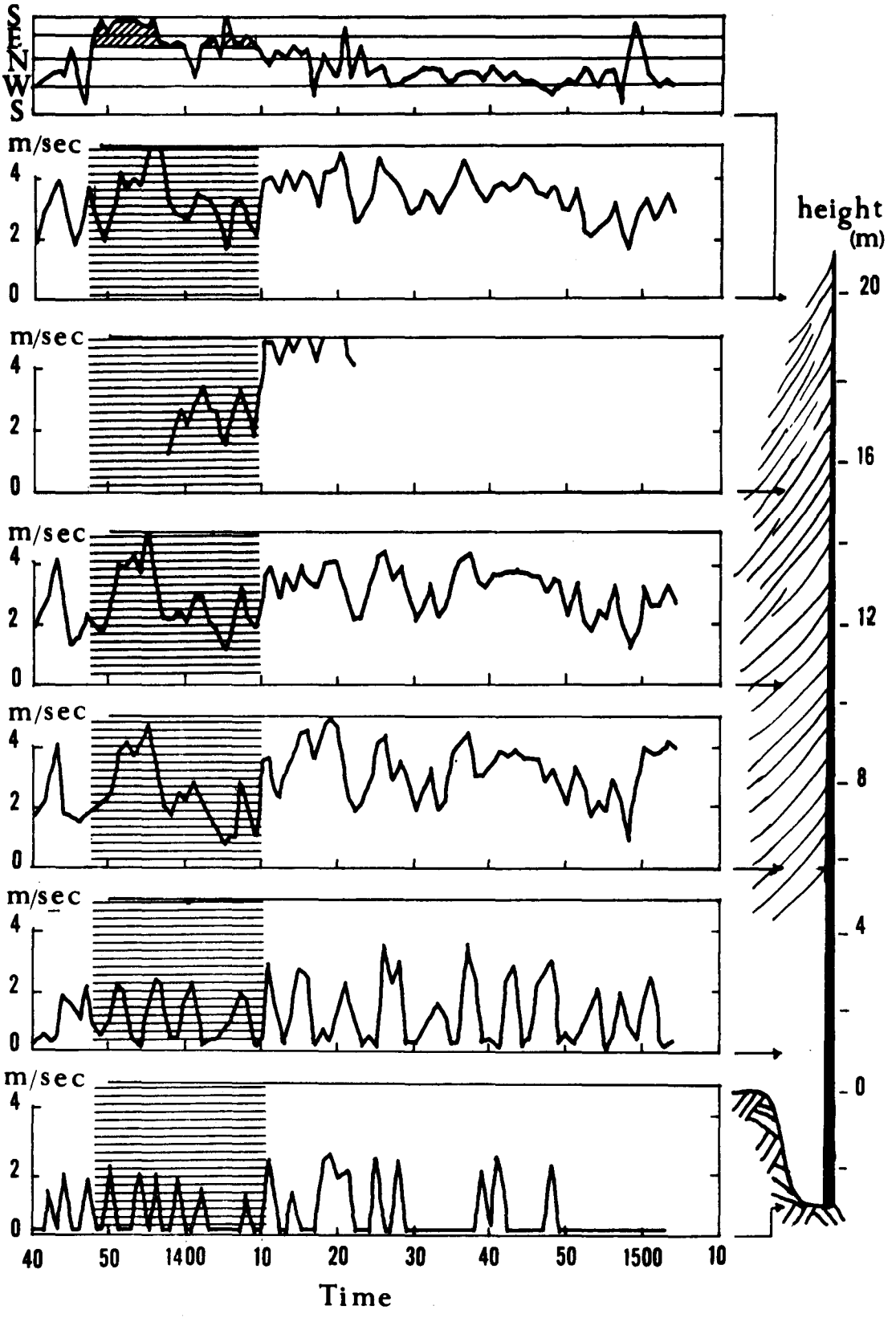


Fig. 8 Wind direction and speed monitored on the southeast corner of the broadcast fire on Pack Forest, June 25, 1968.

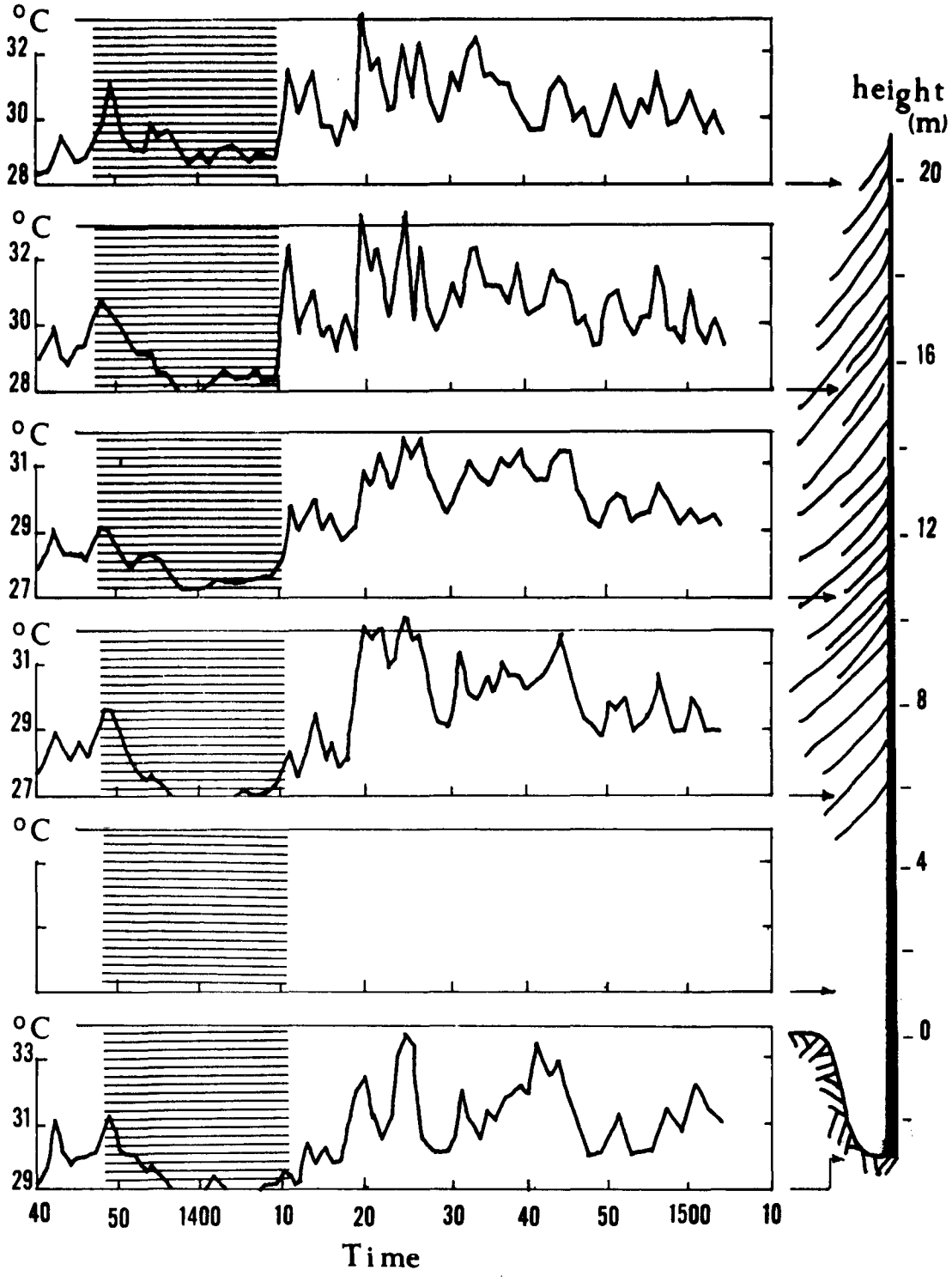


Fig. 9 Air temperatures monitored on the southeast corner of the broadcast fire on Pack Forest, June 25, 1968.

TABLE 10. Particulate loading and percent extractable obtained with high volume samples before and during the broadcast slashburn at Pack Forest, La Grande, Washington, June 24-25, 1968.

Material Number	Collection Period	Particulate	Extractable Percentage
		μ g/m^3	
88	1000 24 June 0923 25 June	64	6.4
73	0900 25 June 1334 25 June	160	22.0
87	1334 25 June 1430	1150	30.8
86	1431 25 June 1629	1510	34.2
85	1630 25 June 1827	950	25.4

This may be due to increased vehicular traffic in the area by study personnel. At least two other slash fires in the vicinity were noted by personnel in the aircraft prior to ignition. Particulate matter from these fires may also have increased the pre-fire background as well as the extractable percentage.

The problem of visibility reduction in the Northwest can be visualized when average particulate loadings above major U.S. cities are compared (Table 11). The Northwest atmosphere is typified by good visibility and relatively

TABLE 11. Suspended particulate matter, 1961 (Public Health Service, 1966)

City	Particulate	City	Particulate
	μ g/m^{-3}		μ g/m^{-3}
Chicago	190	Cleveland	136
New York City	173	Washington	128
Philadelphia	173	Detroit	118
Milwaukee	146	Dallas	92
Baltimore	142	Seattle	87
St. Louis	141	Atlanta	84
Pittsburgh	137	Miami	54

low particulate loads. Thus, any increase in particulate loading and subsequent decrease in visibility, especially in the direction of the surrounding mountains, is readily noticed by both the inhabitants and news media in the area. This problem is not as severe in other areas, i.e. New York, Chicago, etc., where visibility is typically much lower.

Plume characteristics are shown by aerial soundings in Fig. 10. Location of each sound is shown in Fig. 1. The first sounding, 1215, was made during the flight from Seattle to the experimental site. The local industrial pollutants appear to be concentrated in the low level inversion between 300 and 600 m. These data are summarized in Table 12.

TABLE 12. Summary of aerial particulate soundings associated with the experimental fire, 25 June 1968. Refer to Figure 1 for location.

Time	Location	Altitude	Particulate		Background	Average Meteorological Range
			Average	Peak		
		m	---	$\mu g\ m^{-3}$		km
1215	36 mi. N.E.	152- 488	48	129	30	2.5
1240	over burn	579- 823	60	66	21	2.0
1431	2.4 mi. N 72E	914-1584	690	1980	18	0.5
1503	10.6 mi. N 60E	1310-1524	186	216	18	2.3
1530	19.8 mi. N 39E	1524-1768	123	181	12	3.9
1722	17.5 mi. N 18E	244-1555	58	84	3	19.0
1742	25.1 mi. N 4E	457-1494	27	75	3	17.0

Average particulate loading prior to ignition was about the same over both the fire site and over the Seattle industrial area. However the peak loading was much greater over the industrial area. Significantly, the 1722 and 1742 particulate loadings near and over Puyallup (primarily residential and light industry) were not increased above that observed over the Seattle industrial area before the fire, even though the plumes of at least three slash fires had drifted over the area. The particulate sample periods from 1334 to 1827 in Table 10 generally represent the three fire stages. Between 1334 and 1431 (stage I), particulate loading increased but the strong central convection column with horizontal inrushing winds carried most of the particulate aloft. Loading was the greatest during the die down stage II (1431 to 1629) when prevailing wind carried the smoke over the sampling site.

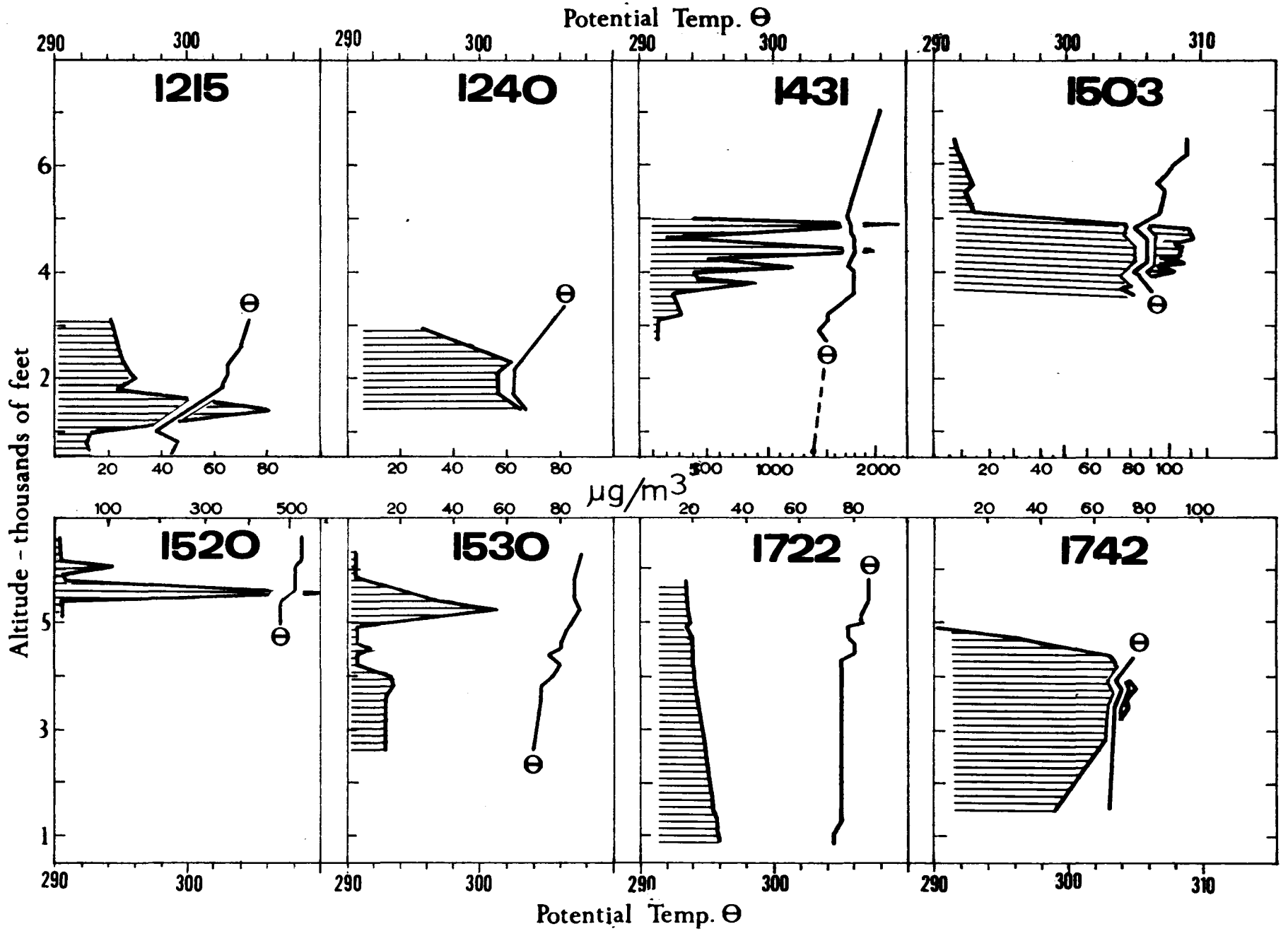


Fig. 10 Mass of suspended particulates and potential temperature observed during vertical soundings of the plume from the June 25 broadcast fire, Pack Forest, 1968.

The extractable percentage also increased. Total particulate decreased in the last period (stage III) and the extractable percentage reduced to the prefire level. The 1240 sounding over the experimental site shows a pronounced inversion between 518 and 640 m and when combined with the 1431 sounding illustrates the atmospheric stability.

The convection column broke through the lower inversion reaching 1524 m before drifting horizontally (1431). As the plume drifted away from the fire it rose slightly from 1524 m to 1737 m and appeared to follow the 308 to 309°K potential temperature surface. The 1742 sounding shows the particulate loading associated with two other lower energy slash fires.

The particulate loading of the plume diluted downwind. This can be shown as the meteorlogical range. The meteorological range is the visual range which would be observed if the air were perfectly homogeneous, and is related to particulate loading by

$$\text{Meteorological range (m)} = \frac{11.7 \times 10^5}{\mu g\ m^{-3}}$$

Meteorological range increased from 0.5 km in the plume at the fire to 4 km at a distance of 32 km downwind. In contrast, the meteorologic range varied from 25 km to 100 km over the Seattle industrial area prior to the burn. The meteorologic range of the background air in the 1431 through 1530 soundings was about 100 km.

The particulate loading appeared to be diluted by about two to tenfold from the ground site to the horizontal plume at the fire. When this dilution factor is combined with the CO_2 dilution factor from the fire to the ground sampling net of 40 to 60, Table 15, the result would indicate a total dilution of 80 to 600 from the fire to the top of the convection column.

4.1.6.2. Carbon Monoxide and Carbon Dioxide The results of carbon monoxide and carbon dioxide analysis are shown in appendix 9.1.1. for the broadcast fire and appendix 9.1.2. for the pile fire. The data for the broadcast fire are summarized in Table 13.

The CO and CO_2 concentrations decreased rapidly from the fire through the sample net. Dilution of hydrocarbons and particulate matter was probably comparable. The distributions of CO and CO_2 downwind from the broadcast fire are shown as isopleths in Figures 11, 12 and 13.

TABLE 13. Concentration of major plume components from June 25, 1968 broadcast fire, Pack Forest.

Sample location	Flames 850°C	Flames 500°C	Flames 500°C	Line 1		Line 2		Line 3		Av.: All Lines		1431 Sound (4 km downwind 1800 m)
	ppm	ppm	ppm	ave. ppm	sd.	ave. ppm	sd.	ave. ppm	sd.	ave. ppm	sd.	ppm
CO	917	4315	8104									0
Period I				8.1	3.2	5.2	3.8	5.2	2.6	6.5	3.4	
Period II				18.7	10.3	10.0	3.3	6.8	1.1	13.8	9.7	
Period III				6.5	2.8	7.6	0.6	5.6	3.8	6.6	2.7	
CO_2	31000	22000	40000									330
Period I				561	97	620	251	480	37	555	149	
Period II				626	154	665	232	575	127	625	164	
Period III				530	118	519	93	596	188	543	129	
$CO/(CO_2-330)$ (average)	0.029	0.194	0.203									
Period I				0.039		0.024		0.035		0.034		
Period II				0.072		0.036		0.033		0.054		
Period III				0.045		0.048		0.066		0.051		
Particulate				$\mu g/m^3$								$\mu g/m^3$
Period I				1150								690
Period II				1510								
Period III				950								
Methane												
Period I												
Period II				2				10				2
Period III				2								
Methanol (Period II)				1.92								.45
Benzene (Period II)				.03								.00
Toluene (Period II)				.40								.04

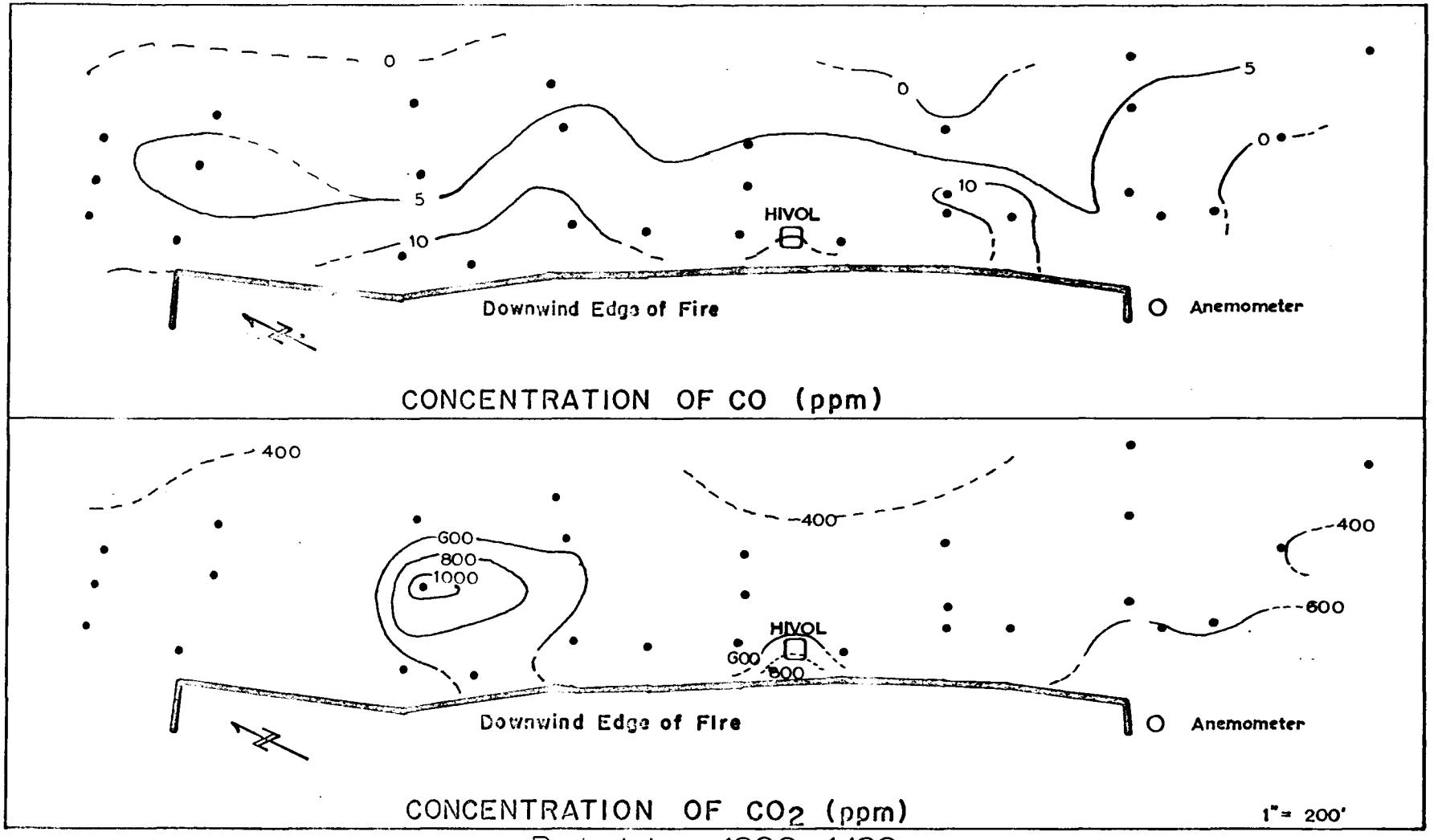


Fig. 11 Horizontal distribution of CO and CO_2 during Period I of the June 25 broadcast fire, Pack Forest, 1968.

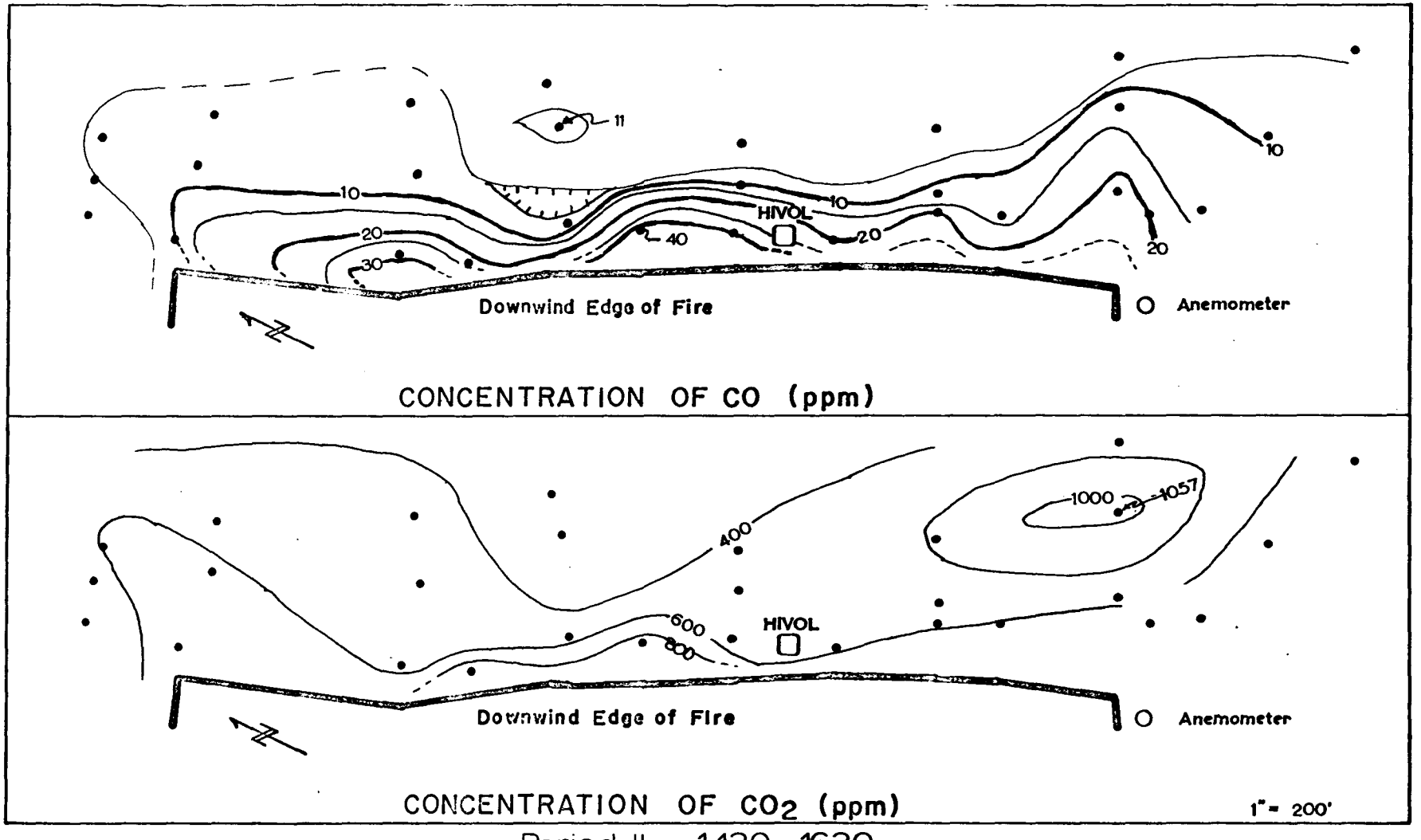


Fig. 12 Horizontal distribution of CO and CO_2 during Period II of the June 25 broadcast fire, Pack Forest, 1968.

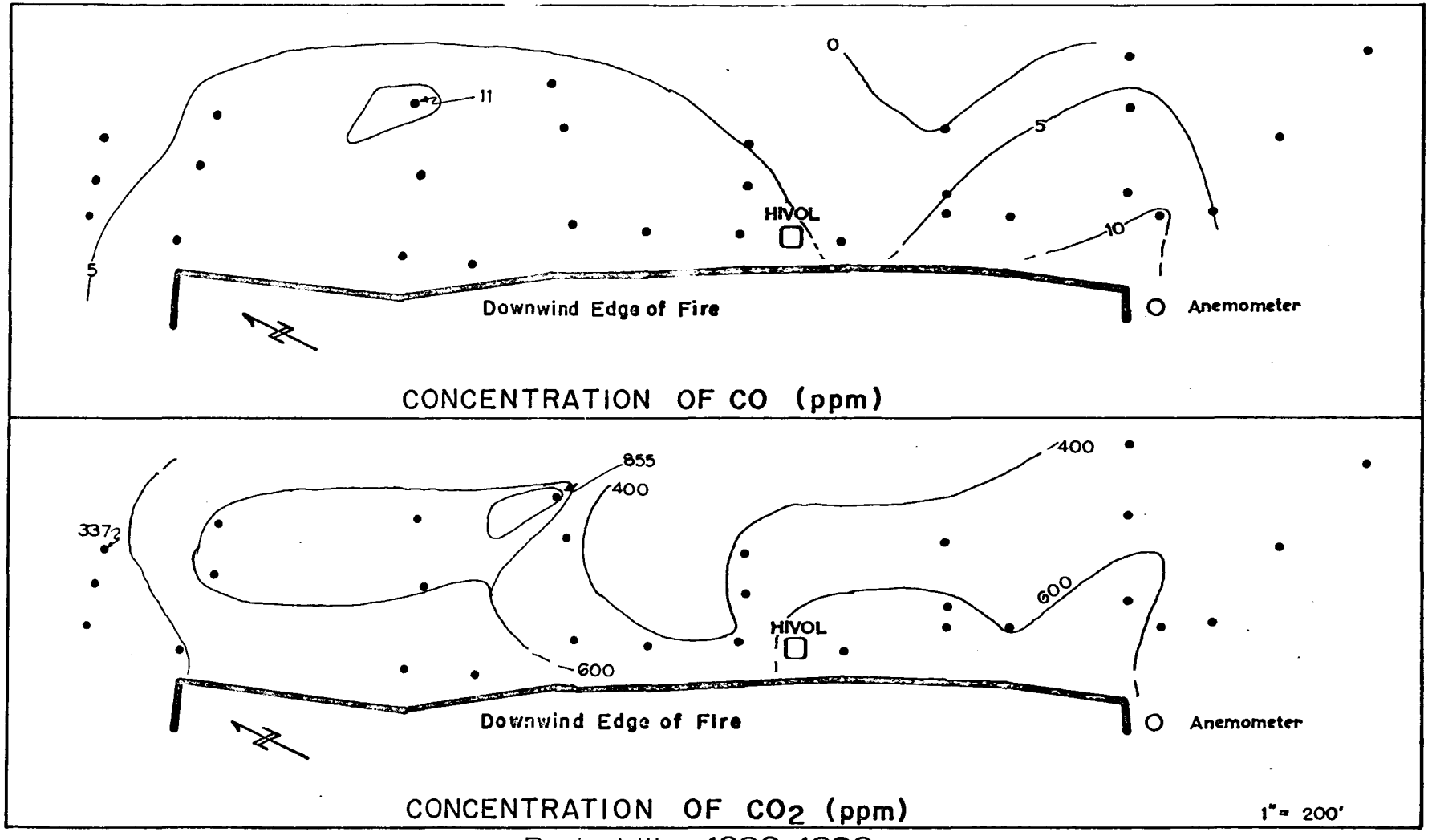


Fig. 13 Horizontal distrubution of CO and CO_2 during Period III of the June 25 broadcast fire, Pack Forest, 1968.

The concentration from the flames, Table 13, to the first line of the sample net changed by a factor of about 520 to 980 for CO, and from 40 to 60 for CO_2. This may indicate that CO underwent further oxidation from the fire to the sample net.

The particulate loading changed by a factor of about 2 from the high-volume filter (period I) to the plume (1431 nephelometer sounding). The average concentration of all hydrocarbon gases changed by about the same factor as the particulate loading from station 9-1, near the high-volume filter during period I, to the airborne grab sample taken just prior to the 1431 sounding. These changes are summarized in Table 14.

TABLE 14. Concentration ratios for various smoke components from June 25, 1968 broadcast fire, Pack Forest.

Component	Flame : Sample Net	Sample Net : Aircraft
CO	520 -- 980	83
CO_2	40 -- 60	unknown
Particulates	unknown	1.67
Hydrocarbons (all gases)	unknown	2.7

No CO was detected in the 1431 grab sample from the aircraft. The CO_2 concentration in the same sample was 330 ppm. The oxidation of CO may have reduced its concentration from an expected 4 ppm to below the detection limit of 1 ppm. Assuming both the sampling and analysis to be reliable and 0.1 ppm to be the maximum undetectable concentration of CO, the minimum change in CO concentration from the sample net to the aircraft would be 83. This change in CO concentration is assumed to be due to oxidation. If the CO_2 concentration changed by the same factor as the particulate and hydrocarbons, the measured CO_2 concentration at the aircraft should have been 60-ppm above ambient CO_2 concentrations. However, no ambient measurements were made.

This sample was taken from an aircraft flying within the plume. If it had been a true point sample, then there is a reasonable chance that the sample was taken from a pocket of unmixed ambient air within the plume. However, the tank in which the sample was taken requires about ten seconds to fill. If the plane was moving at 40 m sec^{-1} (90 mph), then the sample was taken over a 400 m segment of the plume.

Integration of the sample over this distance should provide detectable quantities of both CO and CO_2 if present in greater than ambient concentrations.

The change in the ratio of CO to CO_2 during the fire is apparent in Figure 14. CO versus CO_2 concentration at each point in the sample net is plotted for each period. The slopes of the CO/CO_2 ratios obtained from the 500 and 850° flame gases are indicated by the dashed lines. The smoke in period I apparently originated from flames between 500° and 850°C. However, in period II, several of the samples taken along line 1 fall very close to the slope of the cooler flame.

Ventilation was available for fuels in the interior of the burn because of turbulence associated with the stage I convection column. The gradient wind which predominated in stage II provided less interior ventilation. The better interior ventilation during period I plus the rapid consumption of flash fuels (0-1 cm), created higher temperatures and more complete combustion during stage I. During stage III, almost all of the finer fuels had been consumed. With the exception of smoldering duff, the fire was confined to small, well-ventilated, and compact piles of heavier fuels in which flame temperatures were again higher, and combustion more complete than during stage II.

The CO/CO_2 ratio from the 850° flame gases approximately equals the CO/CO_2 ratio from laboratory combustion of Douglas-fir slash, section 4.3.2. This indicates that both the temperatures and the degree of combustion were approximately the same in the field during stage I and under lab conditions. The strong convection column of the Stage I fire created return eddies which provided a strong backwind around the perimeter of the fire. The plume components during this stage therefore were transported through the sample net from line three (most distant) to line one and back to the fire. When the convection column could no longer penetrate the inversion during stage II, the gradient wind carried the plume directly across the downwind fireline and through the sample net from line one to line three.

The stage II plume underwent rapid and apparently non-uniform dilution from the fire to the first line of samplers in the sample net. From line two through the remainder of the sample net, CO, CO_2, and probably the other plume components as well, underwent uniform and less

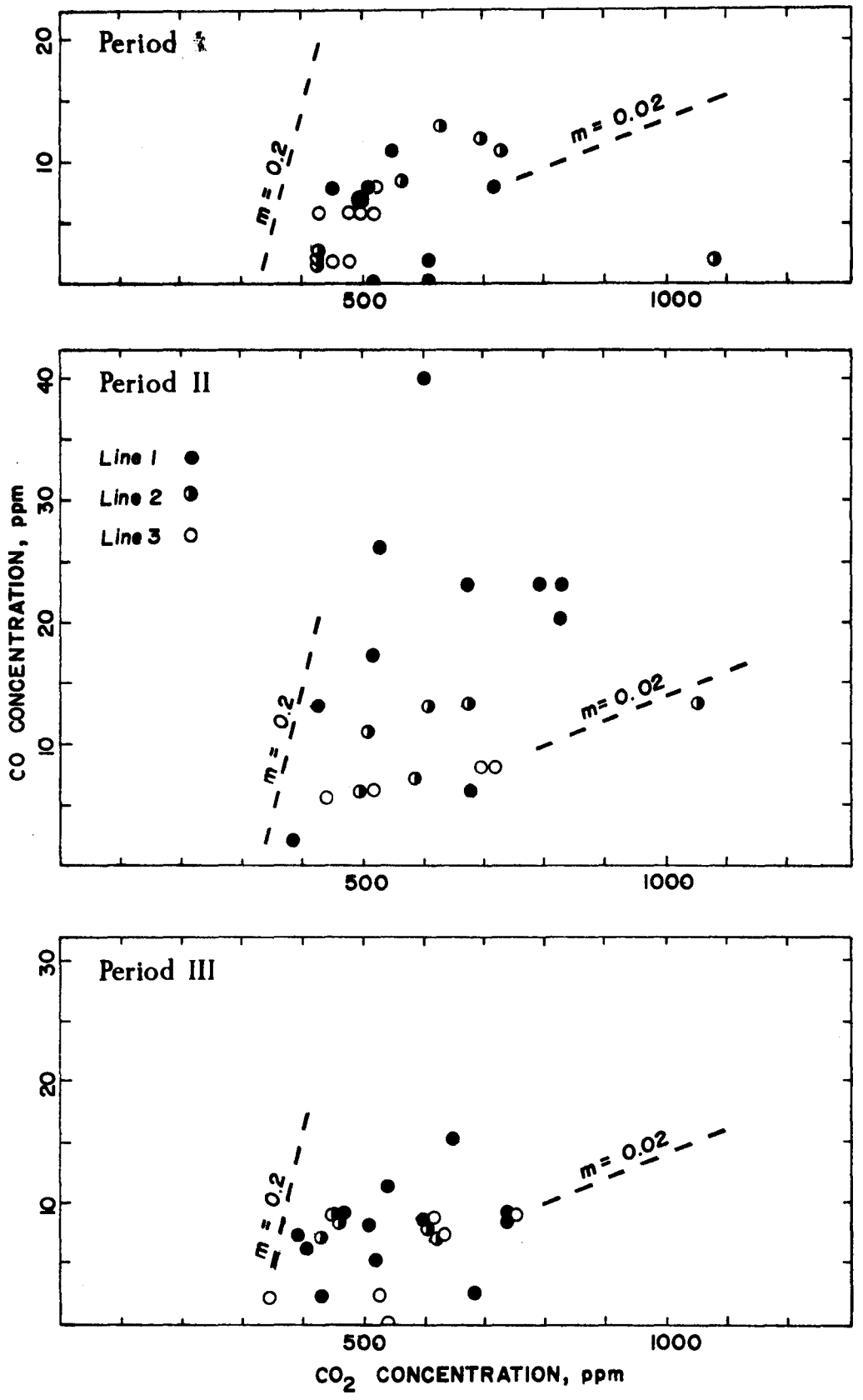


Fig. 14 Concentration of CO vs. CO_2, by period, for smoke collected in sample net from June 25 broadcast fire, Pack Forest, 1968.

rapid dilution. Five points in Fig. 14 which represent samplers on line one lie on a line almost identical with the slope of the CO/CO_2 ratio from the 500° flame gases. The slope of the regression of all points along line one is much less -- 0.025. The slope of the regressions for all points on lines two and three are 0.009 and 0.008 respectively -- identical for practical purposes. The CO-axis intercepts of the two regressions are 3.85 and 2.01 for lines two and three respectively. This downward shift and constant slope of the regression would be expected for two gases diluting equally.

Infrared spectrophotometer analyses of gas samples from the fire area and from the air collected in the plume at 1370 m are shown in Table 15. Samples PB-1, PB-3, and G-11 were taken as close to the fire as a man could walk without a fire suit.

Carbon monoxide readings taken directly in the smoke cloud at ground level with Monoxor Chemical Detector Tubes were 40 ppm early in Period II. Thirty minutes later the readings were down to 20 ppm.

Samples G-4 and G-2 were taken from within the plume with the airplane and show only background levels.

4.1.6.3. Hydrocarbon gases Infrared spectrophotometer analysis of gas samples from the fire area and from the air collected in the plume at 1370 m are shown in Table 15. Description of the sample location

TABLE 15. Infrared spectrophotometer analyses of smoke samples June 25, 1968 broadcast fire at Pack Forest.

Component	PB-1[1] ppm	PB-3[2] ppm	G-11[3] ppm	G-4[4] ppm	G-2[4] ppm
Carbon dioxide	490	820	580	330	320
Carbon monoxide	24	58	40	0	0
Methane	4	10	5	2	2
Ethylene	1	1	1	0	0

1/ PB-1, Period 2 (See Fig. 4 for location).

2/ PB-3, Period 2 (See Fig. 4 for location).

3/ G-11, Period 2 (See Fig. 4 for location).

4/ G-2, G-4 collected from smoke plume with airplane.

is given above. Samples G-4 and G-2 were taken with the airplane and

show only background levels of methane. Threshold limit values of pollutants established for 1968 are listed in Table 16. Values of CO and CO_2 in the fire gas samples with the exception of samples taken in the fire were much lower than the limits.

TABLE 16. Threshold limit values of airborne contaminates established for 1968. (American Conference of Governmental Industrial Hygenists, 1968).

Pollutant	Maximum 8 hour Concentration
	ppm
CO	50
CO_2	5000
MeOH	1 000
EtOH	2 000
Acetone	1000
Benzene	25
Toluene	100
Xylene	100

Detailed analyses of gas samples by a combined gas chromatograph-mass spectrometer technique are shown in Table 17. In general the gas concentrations of all of the components are low.

The most significant components appear to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol and ethanol. Acetone and the aromatic compounds benzene and toluene also appear in most of the samples. Several unsaturated compounds in addition to ethylene and propene were identified but the quantities found were relatively low.

The activated charcoal results represent a much larger sample of air than the bag or tank samples. Because of this many compounds were detected which could not be seen in the small samples. Only compounds with concentrations of 0.01 ppm or greater have been included in Table 17 because of the uncertainties in identification at lower levels and also the increased likelihood of seeing background contaminants instead of compounds from the burn.

TABLE 17. Combined gas chromatograph-mass spectrometer analysis of smoke samples from June 25, 1968 broadcase burn, Pack Forest.

Component	Activated Charcoal	Sample location						
		A-3[1]	I-1[2]	E-1[3]	PB-1[4]	G-11[4]	G-4[5]	G-2[5]
	ppm							
Ethylene	.03	.07	.05	.01	.99	1.05	.04	.09
Ethane	.01	.02	.02	.00	.50	1.25	.02	.05
Carbonyl sulfide	.00	1.00	.50	.50	.00	.000	.00	.00
Propene	.13	.02	.01	.00	.34	.70	.60	.01
Propane	.09	.01	.01	.CO	.21	.60	.01	.02
Methanol	.00	3.07	1.92	1.60	1.03	2.86	.45	.34
Freon 12	.01	..00	.90	.00	.00	.00	.00	.00
Acetaldehyde	.00	.04	.02	.03	.00	.00	.00	.00
Isobutane	.01	.00	.21	.00	.00	.00	.00	.00
1-Butene	.16	.05	.00	.08	.00	.00	.00	.00
Ethanol	.00	.18	.26	.06	.14	.10	.06	.15
Furan	.04	.00	.00	.00	.12	.45	.00	.00
Acetone	.00	.01	.05	.01	.24	.37	.02	.23
Dichloromethane	.01	.65	.48	.11	.00	.00	.00	.00
Dichloroethylene	.01	.00	.00	.00	.00	.00	.00	.00
N-Pentane	.01	.00	.04	.01	.00	.00	.00	.00
2-Pentene	.00	.02	.02	.00	.00	.00	.00	.00
2-Methyl Furan	.00	.00	.00	.00	.03	.17	.00	.00
Ethyl Acetate	.00	.00	.00	.00	.39	.80	.03	.12
Benzene	.07	.04	.03	.03	.09	1.79	.00	.01
2,4-Dimethyl 2-Pentene	.00	.02	.02	.00	.00	.00	.00	.00
N-Heptane	.00	.00	.00	.00	.01	.72	.01	.01
1,1,2 Trichloroethane	.00	3.42	.44	.21	.00	.00	.00	.00
Toluene	.01	.07	.40	.03	.11	.09	.04	.02
Xylene	.00	.04	.07	.00	.00	.00	.00	.00

1/ A-3 taken during Period 3

2/ I-1 " " " 2

3/ E-1 " " " 3

4/ See Fig. 4 for location of PB-1 and G-11.

5/ See Fig. 1 " " " G-4 and G-2.

A number of compounds were detected that are known to have been or suspected to have been introduced accidentally. Freon 12, for example, was found in samples near the nephelometer which employs this gas in its operation. Carbonyl sulfide was found only in bags sealed with black rubber stoppers. 1,1,2 Trichloroethane was found only in those plastic bag samples which were not analyzed soon after collection. In retrospect a number of anomalies in the data might be ascribed to gradual permeation into and out of the plastic bags. Permeation problems should not occur in the stainless steel tanks or in the activated charcoal sample which was stored in a sealed glass container until analysis. In future studies of this kind special precautions should be taken to avoid potential changes in the samples while in storage.

4.2. Pile fire

4.2.1. Carbon Monoxide and Carbon Dioxide

In contrast to the broadcast fires, the pattern of combustion and emission of CO and CO_2 was nearly constant in the pile fire burned July 11. Flame temperatures were higher and combustion was more complete. The fire was hot enough to ignite adjacent stumps and duff. Smoke from these spot fires was drawn into the plume of the pile and interfered with plume gas measurements.

The results of the CO and CO_2 analysis on samples taken from the fire are plotted in figure 15. The CO/CO_2 ratio is relatively constant throughout the fire, except where smoke from the spot fires obscured it. In addition to its relative constancy, the CO/CO_2 ratio for the pile fire was considerably lower than the average for the broadcast fire, as expected.

The ratios obtained from the pile are lower than from an 850° flame in the broadcast fire, lower than the average in the sample net for period I, and lower than that obtained from the laboratory burn. This suggests that laboratory analysis does not take place under conditions which are any better for complete combustion than those which can occur in the field. That piled slash burns hotter and cleaner than broadcast slash is no revelation. However, fuel arrangement in laboratory burning experiments might be adjusted to give results closely paralleling field conditions.

4.2.2. Photography

Motion picture film of the pile fires taken at azimuths 90 degrees apart were used to study: 1) the three dimensional trajectory of four balloons; 2) the two dimensional velocities of flames and smoke; 3) the diameter of the flames at different altitudes; 4) the development of eddies and fire blobs.

The results of three dimensional trajectory of four balloons and several two dimensional velocities of flames and smoke are summarized in figure 16. Although flame speed of 18 m sec^{-1} and smoke speed of 15 m sec^{-1} were observed, the greatest frequency of flame speed appeared to be 3 m sec^{-1} and represented laminar flow. In contrast the speeds between 11 and 18 m sec^{-1} represented extremely turbulent motion with strong horizontal components and erratic changes.

The colored motion pictures were also used to determine relative flame temperatures. For future work three color steps should be calibrated. This would result in flame temperature and possibly air composition data. One series of determinations is shown in figure 17. Three distinct portions of a free flame are described:

1. The inner, dark, reddish, i.e., "cooler" portion, which corresponds to the darker inner portion of a candle flame. This region seems to receive large amounts of distilled fuel gases as well as solid and liquid particulates from the fuel bed below. Oxygen supply is insufficient and the mixture is very "rich". If portions of this "cooler" stream accidentally escape directly into the air after flaming-out, one can observe a substantial flow of smoke. This seems to be the more important source of gaseous, liquid and solid air pollution.

2. The yellow portion of "intermediate" temperature has much better oxygen supply from sideways entrainment of fresh air. The mixture is less "rich" and the high radiation emission is due to large amounts of glowing particulates which are partially consumed in this part of the flame.

3. Once in a while small peripheral sections of bluish-white incandescence are seen. These hottest portions may very well reach a stoichiometric mixture and therefore temperatures may well exceed 1000°K. In a candle flame this portion is seen as a very thin blue mantle wrapped around the yellow flame. In this mantle the melting point of platinum, 2000°K, is exceeded, as observations show. No smoke (solid or liquid light scattering particulates) issues from these hot portions. These white blobs do not contribute to air pollution.

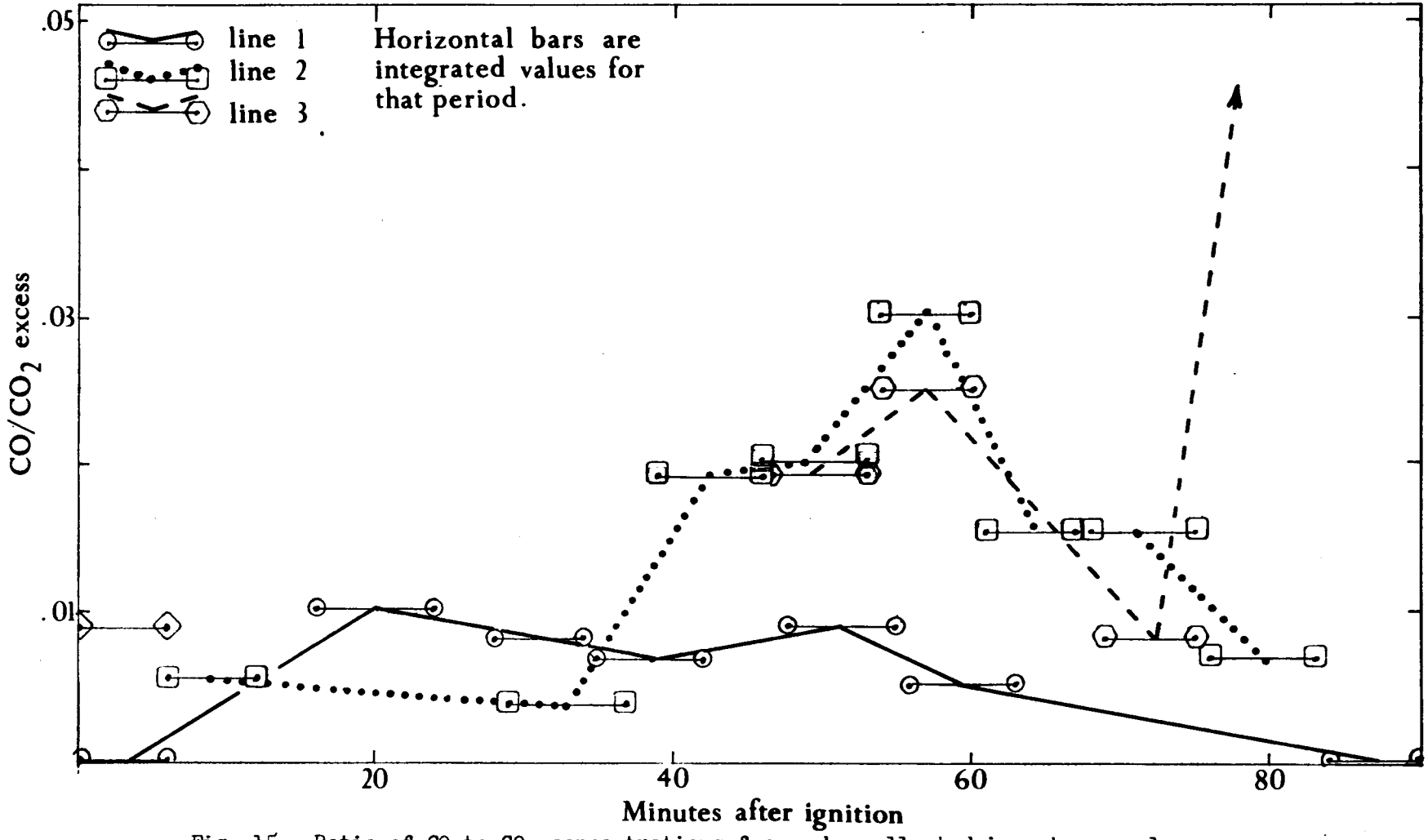


Fig. 15 Ratio of CO to CO_2 concentrations for smoke collected in water samples from July 11 pile fire, Pack Forest, 1968.

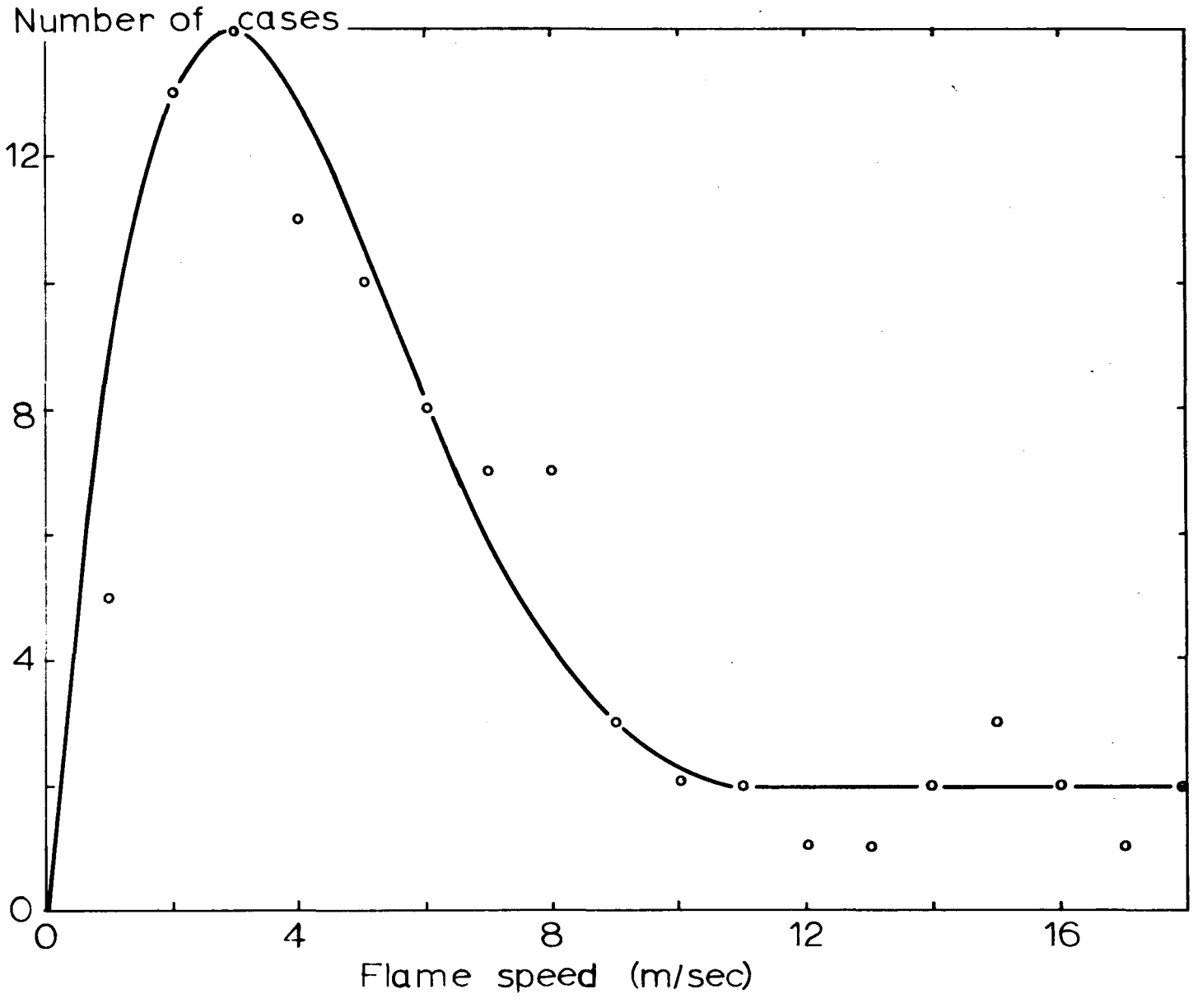


Fig. 16 Frequency of flame and smoke speeds observed from photography.

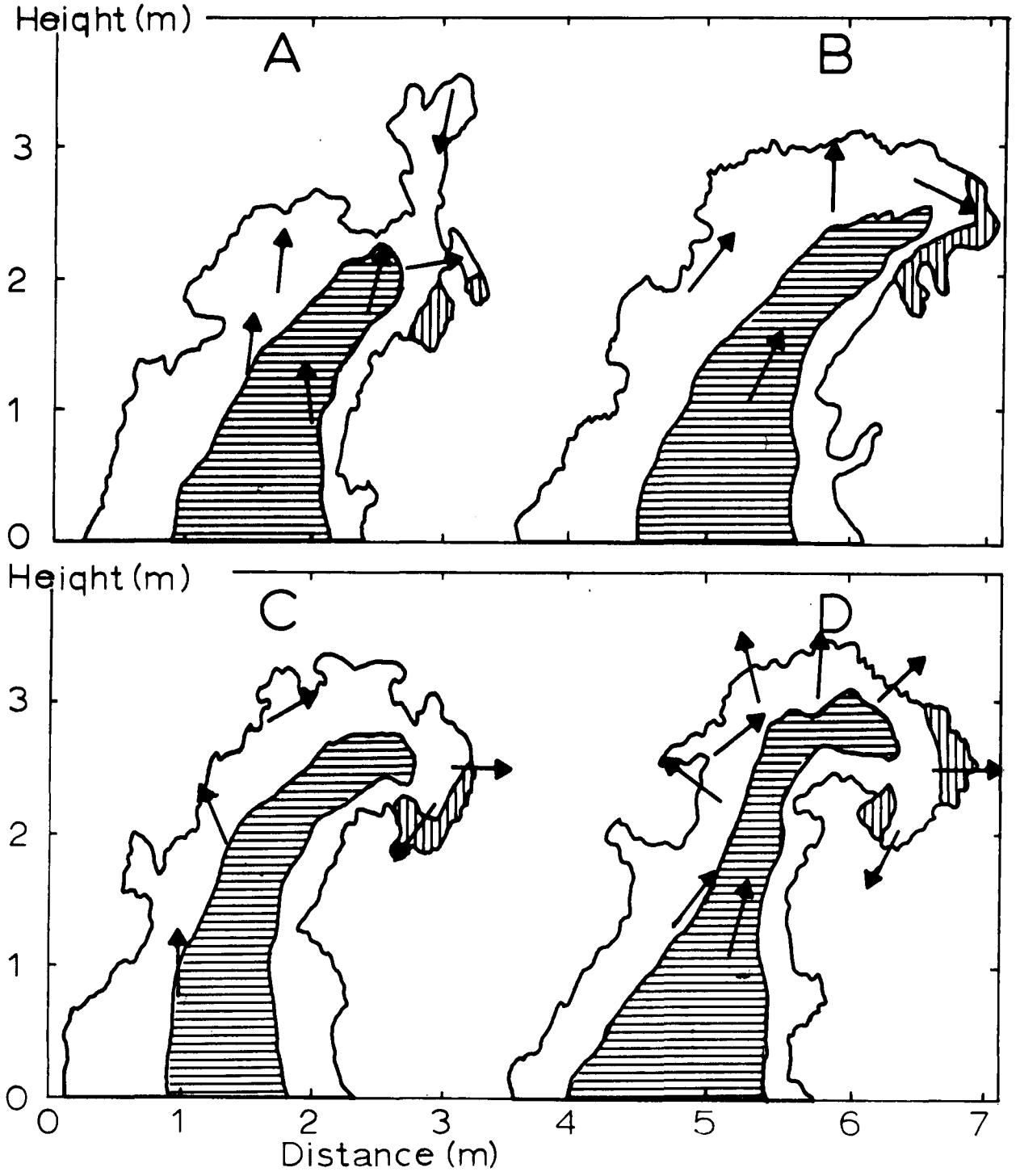


Fig. 17 Relative flame temperatures as determined from colored motion pictures. Horizontal lines represent cooler portion, clear area represents intermediate temperatures and vertical lines represent hottest temperatures.

4.2.3. Modeling open fires

The three pile fires studied in this project were roughly cubical beds of packed wood. The resulting flame diameter was slightly smaller than and somewhat larger in height than the fuel bed. In these relative portions they are quite different from a conflagration such as Hamburg fire where fire diameter far exceeded flame height which again far exceeded height of fuel bed, i.e., the average building. Former tests with G. Fahnestock in 1954 in Priest River, Idaho, using flat fuel bed where no air could enter the fuel bed from below or from the sides showed quite different behavior. In this case the central vertical flame diameter was about 1/5 of fuel bed diameter.

These fires will be discussed with respect to four simple models: a chemical model, a rising air speed model, a geometric model, and a pressure gradient model.

A simple chemical model of a flame may be the burning of one mole of $(CH_2O)_n$ with one mole of O_2 into aliquot numbers of CO_2 and H_2O. Since measured CO_2 rarely exceeds 10 percent of the flame gas volume, a similar amount of combustion-created H_2O may be present. Burnable wood in general contains but a few percent of free water. The main mass of gas moving through a fire is therefore nitrogen. The total molar mass increase will barely exceed 10 percent. Since the volumes involved are strongly controlled by temperature and temperatures are not too well known, changes in masses moved as well as changes of average molecular weight may be neglected.

In a simple geometrical model, the flaming portion of a compact fire may be likened to a vertical cylinder of flame height z_0 and radius r_0. Into its periphery an air volume of $\rho_0 \cdot u_0 \cdot 2\pi r_0 \cdot z_0$ (m^3/sec) will be moved and a nearly (see chemical model) equal volume $\rho_1 \cdot w_1 \cdot r_0^2 \pi$ will leave at the top level of the flames. ρ is air density. The coordinates used are as follows: x is the direction from an observer into the fire; v is a horizontal component perpendicular to x; z is the mean height; u, v, and w are vector flows in the x, y and z directions. "Gradient" wind is the wind outside of the fire. Subscript 0 means near the fire border.

The speed of wind into the fire or fire storm may be obtained by equating the above products.

$$U_0 = \frac{\rho_1 \, w \, r_0}{\rho_0 \, 2z_0} \qquad (1)$$

With environmental temperatures of 300°K and flame temperatures of 900°K $\rho_1/\rho_0 \cong 1/3$ or

$$U_0 \cong \frac{w r_0}{6 z_0} \tag{2}$$

Using observed values from the pile fires of r_0 = 6m, z_0 = 10 m, and w = 8 m sec^{-1}, the resulting value of U_0 should be about 0.8 m sec^{-1}. Such wind speeds could be observed only under calm conditions by very careful checking of flame motion.

Assuming values of w= 20 m sec^{-1}, r_0 = 1200 m and z_0 = 100 m for the Hamburg conflagration, the resulting horizontal wind speed should be approximately 40 m sec^{-1}. Values of 20 m sec^{-1} have been reported near some ground conflagrations. The strongest winds will occur above the surface and will exceed 20 m sec^{-1}.

A simple model for obtaining the rising speed of flame air, w_1, could depict the flame as either a rising balloon of hot air or a vertical cylinder of radius r_0. At equilibrium, the forces of gravity and drag are equal. For a sphere

$$\Delta\rho g \frac{4\pi r_0^3}{3} = \rho_0 \pi r_0^2 w^2 \tag{3}$$

where $\Delta\rho = \rho_0 - \rho_1$. Using the values for the pile fires (4)

$\Delta\rho/\rho_0 = 2/3$ then

$$w = \left(\frac{\Delta\rho}{\rho_0} g \frac{(4r_0)}{3}\right)^{1/2} \cong (10\, r_0)^{1/2} \tag{5}$$

It is doubtful whether the whole flaming area of Hamburg of r_0 = 1200 m created one continuous ball or indeed if the above equation can be applied to such large areas. Solving the above equation with the pile fire data w $\cong$ 7 m sec^{-1} was anticipated and observed (see section 4.2.2.). Finally, a w = 4 m sec^{-1} could be expected from the California Project Flambeau fires of r_0 = 160 m. Using pulsed radar, w = 20 m sec^{-1} was observed.

The vertical motion, w, is not the cause of the fire wind. It is the result of the horizontal pressure gradient ∇p created by the visible flame air and smoke air. Maximum U_0 and ∇p will be created under calm

conditions because all of the hot air is above the fire. Increasing gradient winds will cause the hot air column to tilt thereby reducing U_0.

According to Buettner (1967), the general equation for motions can be written as $D(\rho \mathbb{V})/Dt = -\nabla p$ (6)
if we neglect friction and Coriolis forces. Simplifying further by having only component u into a vertical flame wall, we have

$$\partial\mu\ (\rho u)/(\partial x) = -(\partial p)/(\partial x) \qquad (7)$$

or integrated $$\rho u^2 = -\Delta p \qquad (8)$$
if u_g is zero.

The pressure difference, Δp, between free air and fire, near the surface, is $-\Delta p = z_0 \cdot g\, \Delta\rho$ where z_0 is flame height. (9)
Using the same data as before we find $\Delta p = 0.67$ mb for a flame height of 10 m. Combining eq. 8 and 9 we have the fire storm or into-fire wind as

$$u = (z_0\ g\ \Delta\rho/\rho)^{1/2} \qquad (10)$$

or with $g = 10\ \text{m sec}^{-2}$ and $\Delta\rho/\rho = 2/3$

$$u = 2.6\ z_0^{1/2}$$

In the Hamburg fire values of z_0 were in excess of 100 m resulting in $u_0 = 26$ m/sec or more.

A more refined theory should take into account:

a) the conical form of smaller fire flames and the consequent ∇p pattern
b) the combination of equations of motions and of conservation of mass
c) the effect of the shrinking diameter through which air moves into the fire if this is essentially a cylinder or a cone
d) the effect of the step-function of u at the fire border where suddenly ρ drops drastically.

4.3. Laboratory Fire

Results of the microanalysis and the average concentrations of major pollutants during burning of the slash samples are given in Table 18. These data are especially interesting because the absolute quantities of emittants can be monitored more or less completely, and a carbon balance can be written for each fire. Carbon balances recorded on grassy material

TABLE 18. Laboratory analysis* of combustion products from Douglas-fir, Western hemlock, and Western Redcedar slash.

Sample	Sample wt.	Microanalysis** Carbon	Hydrogen	Moisture Content	Smoke	CO	CO_2	C (hydrocarbons)	CO/CO_2	Residue	Carbon balance
				% ODW							
	kg	(% wt)	(% wt)		g/kg	g/kg	g/kg	g/kg			%
Hemlock 1	11.4	63.39	1.82	8.4	2.0	30	1030	1.2	0.02939	1.9	79
Hemlock 2	12.1	67.65	1.73	8.4	2.0	46	1213	1.2	0.03628	1.6	93
(wood)		47.88	6.42								
Douglas-fir 1	8.2	59.67	1.95	7.2	2.3	32	1143	1.6	0.02828	1.5	89
(wood)		46.84	6.46								
Western Redcedar 1	11.0	62.77	1.90	7.2	1.7	56	1554	2.2	0.03636	1.0	109
Western Redcedar 2	11.0	56.98	1.62	7.2	2.2	59	1395	2.2	0.04212	2.9	110
(wood)		47.36	6.49								

*Analysis by E. F. Darley

**Analysis by Elek Micromanalytical Laboratories, P. O. Box 1156, Walteria Sta., Torrance, California 90505

burned in the same fashion typically fall between 95 and 99 percent. Since this was the first experiment with logging slash materials, the rather large variations in carbon balance for these fires are largely unexplained.

Trends of temperature from five laboratory fires are shown in figure 18. The temperature curves show different burning characteristics for similar quantities of fuel from the same species. The differences are unexplained and could be due to differences of fuel packing and ignition.

4.3.1. Particulate Matter.

Particulate matter production from the five samples are reported in Table 18 as grams of smoke per kilogram of fuel. All samples yielded about the same amount of smoke.

4.3.2. Carbon Monoxide and Carbon Dioxide.

Cumulative CO_2 production curves are shown in Figure 19. For similar species CO_2 production between samples occurred during the equilibrium burning period. More CO_2 was produced by the western redcedar than by western hemlock or Douglas-fir.

Carbon monoxide production from the five samples appeared similar to CO_2 production (Figure 20A).

The ratio of CO to CO_2 from the laboratory fires was similar to the ratio during period I of the broadcast fire (4.1.5.2.) and slightly greater than the ratios from the pile fire (4.2.1.).

4.3.3. Hydrocarbons.

Production of total hydrocarbons is reported as "C" in Table 18. Trends are shown in Figure 20B. Hydrocarbon-production appeared to be greatest from western redcedar with Douglas-fir second and Western hemlock third. Total hydrocarbon production from Western redcedar was similar to that from dry native brush and fruit prunnings as reported by Darley, et al (1966) and much lower than hydrocarbon production in rice and barley straw.

Individual hydrocarbons from the laboratory fires are shown in Table 19.

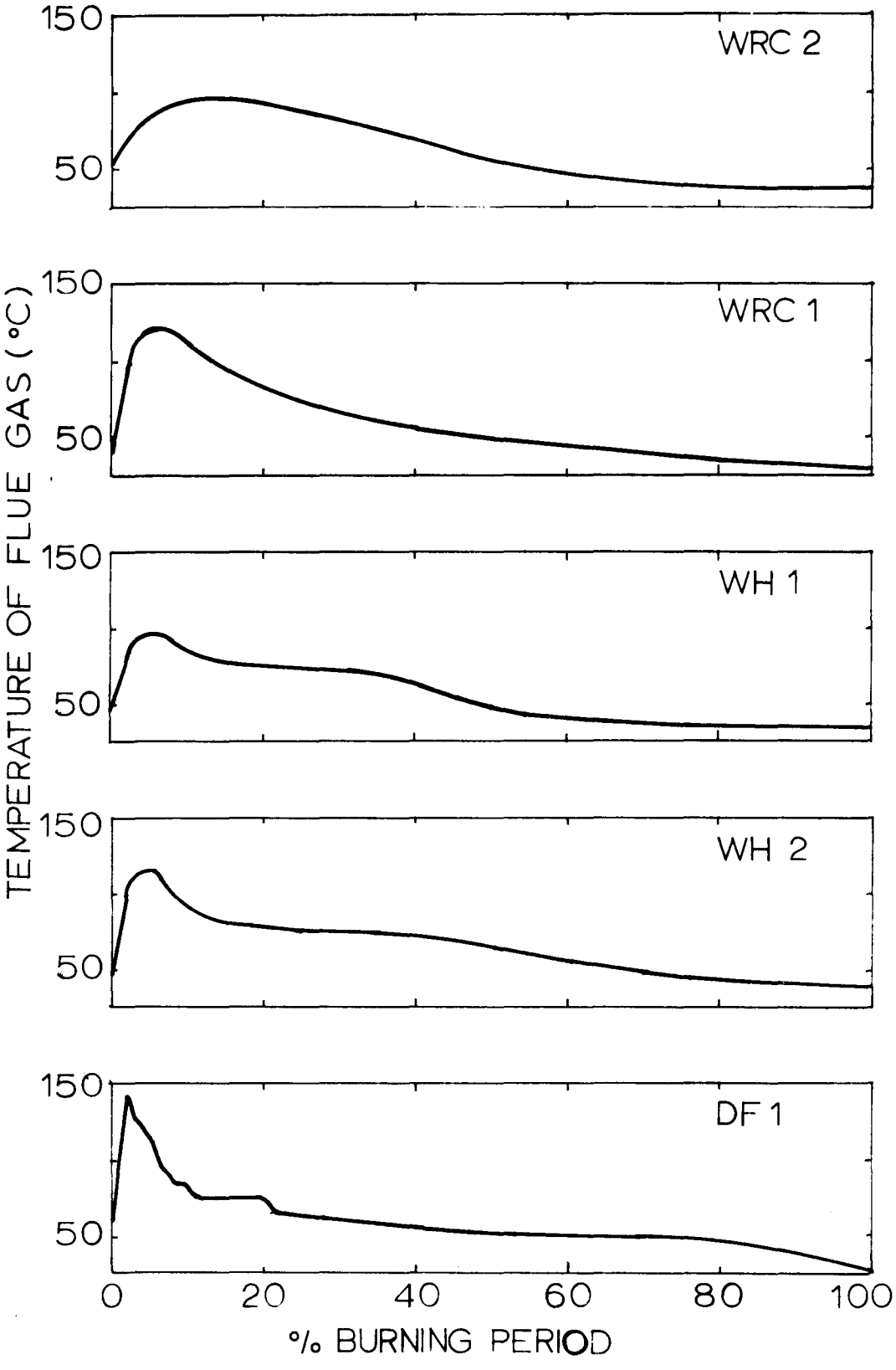


Fig. 18. Gaseous temperature in relation to percent of burning time of fire laboratory samples.

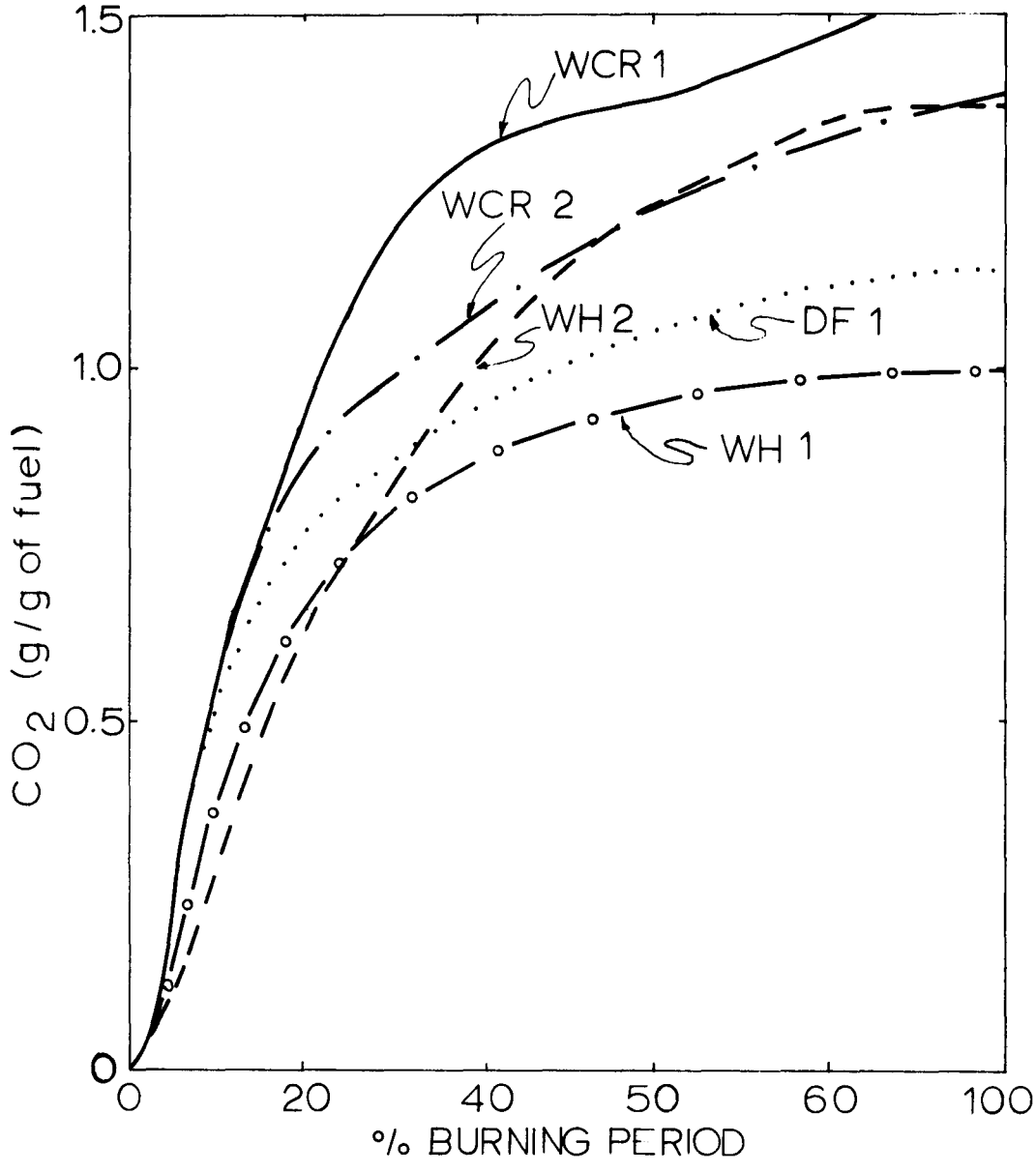


Fig. 19 Cumulative CO_2 production from five laboratory samples.

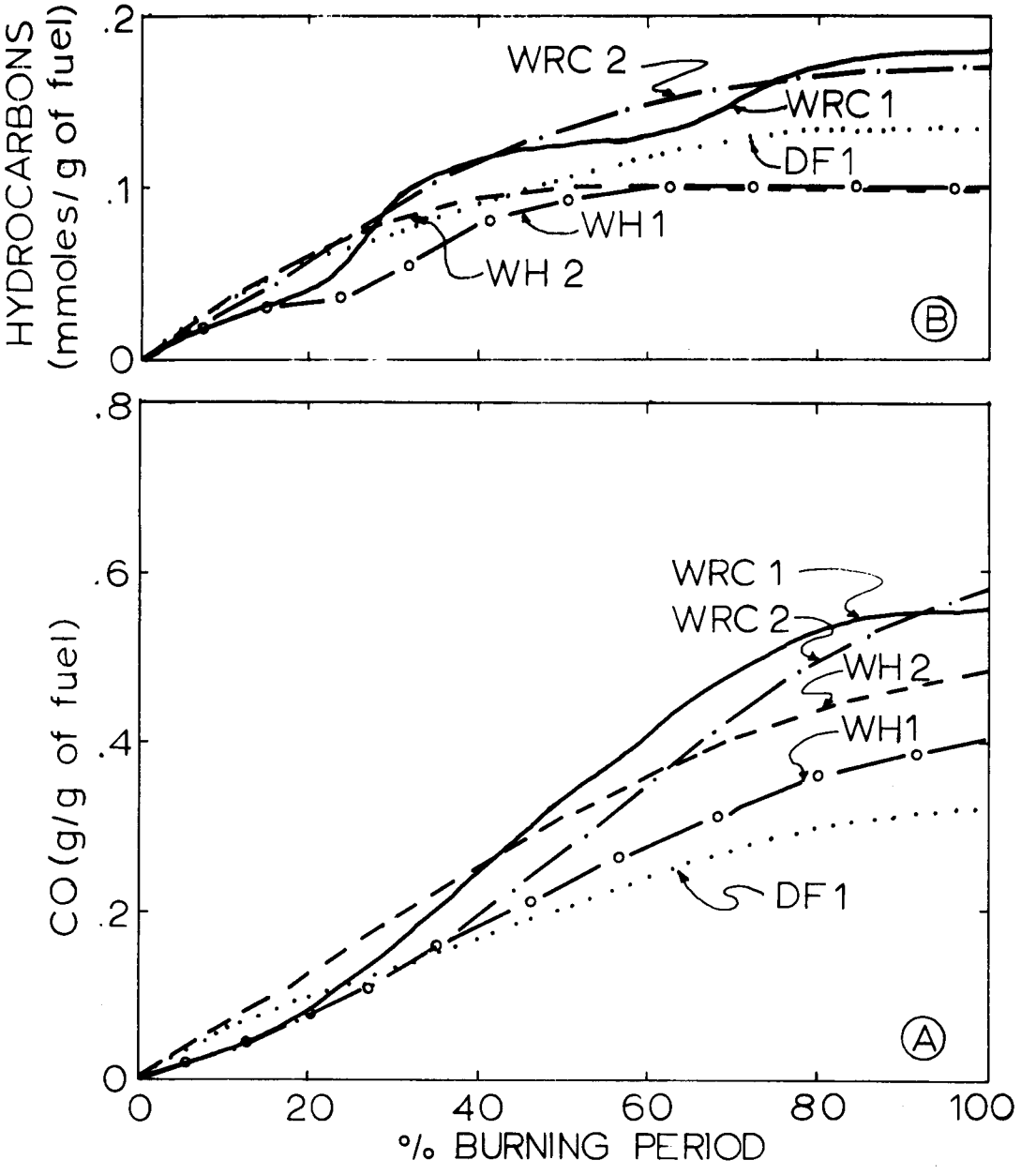


Fig. 20A Cumulative CO production from five laboratory sample.
Fig. 20B Hydrocarbon production from five laboratory samples.

TABLE 19. Gas chromatographic analyses of smoke samples from five laboratory fires in ppm.

Sample	Western Hemlock						Douglas-fir			Western Redcedar					
Sample Number	#1			#2						#1			#2		
Minutes after fire start	2	7	17	1.5	7	18	1	5	16	2	5	16	2.5	8	19
METHANE	3.2	--	13.2	3.2	4.8	8.3	2.0	0.7	9.3	3.5	5.2	11.2	10.0	4.3	7.8
ETHENE	1.0	--	1.4	1.2	0.6	0.6	0.6	0.9	1.0	1.3	0.8	0.9	5.2	0.5	0.6
ETHANE	0.1	--	0.6	0.1	0.2	0.3	0.6	0.3	0.5	T	0.3	0.4	0.7	0.2	0.3
ACETYLENE	0.6	--	0.1	0.7	0.3	0.2	0.3	0.3	0.2	0.7	0.3	0.3	2.5	0.1	--
PROPANE	T	--	0.4	T	2.7	T	T	0.1	0.2	T	0.1	0.3	0.2	T	T
PROPENE	0.2	--	0.5	0.3	0.1	0.1	0.1	0.3	0.5	0.3	0.2	0.3	1.1	0.2	0.2
ISOBUTANE	--	--	T	T	T	T	T	T	T	T	T	T	T	T	T
N-BUTANE	T	--	T	T	T	T	T	T	T	T	T	T	T	T	T
ACETYLENE	0.7	0.1	0.5	0.8	0.2	0.1	0.5	0.3	0.2	0.8	0.3	0.3	2.9	0.3	0.2
1-BUTENE	T	T	T	T	T	T	T	T	T	T	T	T	0.2	T	T
ISOBUTENE	T	T	T	T	T	T	T	T	T	T	T	T	0.1	T	T
TRANS-2-BUTENE	T	T	T	T	--	--	--	T	T	T	T	T	T	T	T
ISOPENTANE	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CIS-2-BUTENE	T	T	T	T	--	--	--	T	T	T	T	T	T	T	T
N-PENTANE	--	--	--	--	--	T	--	--	--	--	--	--	--	--	--
3-METHYL BUTENE-1	T	T	T	T	T	--	T	T	T	T	T	T	T	T	T
1,3-BUTADIENE	T	T	T	T	T	T	T	T	T	T	T	T	0.3	T	T
1-PENTENE	T	T	--	--	--	--	T	T	--	T	T	T	T	--	--
2-METHYL BUTENE-1	--	--	--	--	--	--	--	--	T	--	--	--	T	--	--
TRANS-2-PENTENE	--	--	T	--	--	--	--	--	--	--	--	--	T	--	--
2-METHYL BUTENE-2	--	--	--	--	--	--	--	--	T	--	--	--	--	--	--

T = Less than 0.1 ppm. Methane, Ethane, Ethene and Acetylene were analysed using a 5-foot Poropak N column at 60°C. All others were analysed using 36 foot, 10% DMS column at 0°C.

The concentration of individual hydrocarbons obtained from the laboratory samples were essentially the same as those obtained from the broadcast fire (4.1.5.3.). Since the hydrocarbon concentrations were similar, the absolute values in g per kg of fuel from the laboratory can be said to estimate hydrocarbon production from the field.

5. SUMMARY & CONCLUSIONS

The relationship between the current practice of slash burning and air pollution was investigated with broadcast and pile fires in the field and laboratory fires. The hypothesis tested was that incomplete combustion and consequently greater emissions result from low temperature fires. In our experiments the broadcast fires represent low temperature fires while the piles and laboratory fires represent higher temperature fires. These experimental fires were investigated with respect to burning characteristics, gaseous, hydrocarbon and particulate emissions. The results of each fire are summarized individually.

The broadcast burn was centerfired using power boosters. In 15 minutes a strong convection column had developed which penetrated a lower inversion at 640 m and sheared at 1370 m. The convection column began to lay over with the prevailing wind 25 minutes after ignition and by 90 minutes after ignition only disorganized small sources of smoke remained. From photography and meteorological observations, three fire stages were described, the buildup, die-down and isolated hot spots.

Ground particulate samples indicated an increase of nearly 10 times the background level immediately downwind from the fire during the second stage. The particulate in the smoke plume in the fire vicinity reduced visibility to 0.5 km but at a distance of 19 km from the fire the visibility had increased to the level found over Seattle.

Similarly, high CO and CO_2 concentrations found at the fire site decreased rapidly to ambient conditions in horizontal and vertical directions. CO/CO_2 ratios increased from 0.034 during the buildup stage to 0.051 during the isolated hot spot stage. CO/CO_2 ratios from 850°C flames were similar to those from the laboratory fires.

Hydrocarbon analyses of gas samples revealed low concentrations of 25 components, the most significant of which appear to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol and ethanol. Several unsaturated compounds were found but the quantities were relatively low.

In contrast to the broadcast fire, the pattern of combustion and emission was more uniform in the pile fires. The CO/CO_2 ratios were nearly constant throughout the fire and were lower than from the 850°C flames in the broadcast fire and the laboratory fires.

Analysis of laboratory fires of Douglas-fir, western hemlock and western redcedar revealed three fire stages: the buildup, die down, and equilibrium stage. The length of each stage appeared to be related to the total charge, fuel packing, density, and quality. The burning characteristics of the Douglas-fir laboratory fire were very similar to the broadcast fire. Analyses of the gases revealed CO and CO_2 emissions similar in magnitude to those from burning other agricultural residue. The total hydrocarbon level appeared to be lower. The CO/CO_2 ratios from the laboratory fires were similar to those from the broadcast fire indicating similar degree of combustion.

The results of these tests suggest that broadcast fires can be modeled in the laboratory with respect to burning characteristics, gaseous and particulate emissions from different fuel density, packing, quality and method of ignition. Furthermore, these tests indicate that the air pollution aspects of slash burning can be minimized by establishing a high energy fire with a strong convection column under conditions favorable for rapid atmospheric dispersion. These conditions may be achieved by balancing local fire behavior management with meteorological management of smoke.

Fire behavior management includes techniques of fuel modification, electrical ignition and fuel booster systems, and firing sequences, all aimed at obtaining quick, positive ignition and rapid fire development with complete combustion of unwanted fuel.

Meteorological management may include burning under an unstable atmospheric profile, burning when wind speeds are sufficiently high to advect smoke and wind directions are away from populated areas.

Slash burning may have to be done in all seasons: fall, winter, spring, and summer. Year-long burning may be necessary to obtain enough burning days when the air pollution threat can be minimized by some trade-off between local fire behavior management and meteorological management. In late winter or spring, large fuels may still have high fuel moistures, and fires of short residence time consuming only the smaller fuels -- "quick, hot" fires -- will result. In late summer or fall when heavy fuels are dry residual glowing combustion, as typified by Stage III of this study, may result. Total emissions output may be relatively high over long periods of unfavorable dispersal conditions (night time subsidence and inversions). This type of air pollution threat may be overcome by burning early in the day, establishing a high rate of energy release during this more stable period. Decreasing energy release rates will be

offset by increasing atmospheric instability later in the day. Chances of burnout of all available fuels, including the heavy fuels, will be increased.

In general, the concentrations of gases and hydrocarbons found in gas samples taken under field conditions were similar to those taken under laboratory conditions. Concentration of gases and hydrocarbons diluted rapidly to ambient or background values. Particulate emissions in the smoke plume were high but decreased in 20 km to values found over the Seattle area.

In addition to the air pollution aspects, the following significant findings and developments resulted from this research project: the air-borne version of the integrating nephelometer used in these studies was developed and flight tested; air samplers, capable of operating without power were developed to collect air samples over a period of time; the vacuum oven technique was the most reliable and practical method of determining fuel moisture; and the peak frequency of flame speeds was found to be 3 m sec.

6. FUTURE RESEARCH

Areas of additional research suggested as a result of this project are:

1) Ignition systems for different fuels, weather, and topography to minimize air pollution.
2) Fuel booster systems to achieve rapid high temperature and rate of energy release buildup.
3) Practical methods of energy budget analyses to aid in decision making of prescribed burning time and technique.
4) Climatological study of potential temperature surfaces and drift patterns to aid in scheduling burning.
5) Economic analyses of alternative burning techniques.

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10. APPENDIX

10.1. Carbon monoxide and carbon dioxide data

10.1.1. Broadcast fire

TABLE 20. Analysis of CO and CO_2 collected in water-displacement air samplers during June 25, 1968 broadcast burn, Pack Forest.

Location	Period I		Period II		Period III	
	CO	CO_2	CO	CO_2	CO	CO_2
	ppm	ppm	ppm	ppm	ppm	ppm
A 1	8	450	no data	450	no sample	
A 2	no sample		no sample		no sample	
A 3	6	427	8	697	2	337
B 1	7	495	17	517	8	517
B 2	2	427	7	585	7	630
B 3	7	495	6	526	7	630
C 1	no sample		no sample		11	540
D 1	11	549	26	531	no sample	
D 2	2	1080	6	495	8	607
D 3	2	472	6	436	11	630
E 1	12	697	13	607	8	607
F 1		517	2	382	8	463
F 2	8	562	11	508	7	427
F 3	2	450	no sample		6	855
G 1	6	487	20	832	2	684
H 1	no sample		no data	495	6	405
H 2	6	495	no data	470	8	463
H 3	no sample		no sample		no sample	
I 1	6	472	40	607	2	427
J 1	8	720	23	796	no sample	
J 2	11	729	13	679	no sample	
J 3		495	no data	967		540
K 1			23	832	no sample	
L 1	2	607	23	675	8	742
L 2	2	427	13	1057	8	463
L 3	8	517	8	720	2	526
M 1	8	508	6	675	7	391
N 1		607	13	430	5	517
N 2		405	no sample		no sample	
N 3	6	517	6	495	no sample	

10.1.2. Pile Fire

TABLE 21. CO and CO_2 concentrations in samples taken during July 11, 1968 pile fire, Pack Forest

Line 1 1/			Line 2 1/			Line 3 1/		
Time 2/ Sample Started	CO	CO^2	Time sample started 2/	CO	CO^2	Time sample started 2/	CO	CO^2
	ppm	ppm		ppm	ppm		ppm	ppm
1237	0	449	1240		missing	1239	6	972
1247		missing	1250	2	671	1248		missing
1255	1	416	1258		missing	1325	5	578
1307		missing	1308	1	578	1333	25	1318
1314	1	462	1318	5	578	1340		missing
1321	10	671	1325	2	419	1348	1	439
1327	25	430	1333	5	487	1355	45	1041
1335	25	763	1340	2	449			
1343	2	763	1347	2	449			
1353	0	462	1402	1	462			

1/ Location of sample lines shown in figure 5.

2/ Average sample period was 7 minutes.

10.2. Conversion Factors

1 centimeter (cm)	=	0.0394 in.
1 inch (in)	=	2.54 cm
1 meter (m)	=	3.28 ft.
1 foot (ft.)	=	0.305 m
1 kilometer (km)	=	0.621 stat. mi.
1 stat. mi.	=	1.609 km
1 hectare (ha)	=	2.471 acre
1 hectare (ha)	=	$10^4 m^2$
1 liter (l)	=	0.264 gal.
1 gallon (gal)	=	3.785 l
1 meter per second (m sec^{-1})	=	2.236 mph
1 mile per hour (mph)	=	0.447 m sec^{-1}
1 gram (g)	=	0.00220 lb.
1 pound (lb)	=	453.6 g
1 metric ton (5)	=	1.102 short ton
1 short ton	=	907.2 kg
1 cal	=	0.00397 BTU
1 BTU	=	252 cal

10.3 A WATER-PUMP AIR SAMPLER FOR USE AT REMOTE SITES

S. Pickford, R. Charlson, and K. Buettner

ABSTRACT

A portable air sampler for use where no electricity is available is powered by water siphoned out of a plastic jug. This causes air to be drawn into a mylar sample bag sealed inside the jug. Flow rates are reasonably constant over the sample period, and the system has been used at flow rates from 0.06 to 1 liter per minute. Materials cost is low and large numbers of sample points can be monitored simultaneously.

A WATER-PUMP AIR SAMPLER FOR USE AT REMOTE SITES

S. Pickford, R. Charlson, and K. Ruettner

Most air quality studies are made in urban areas where electricity can be used to power air samplers. In the course of instrumenting a project on the effects of burning logging slash on air quality, we developed a sampling system which is independent of electrical power and can be used to monitor relatively large numbers of sample points simultaneously.

The pumping action is provided by siphoning water from a plastic container at a known flow rate. A similar system was first used by K. Buettner and G. Fahnestock on slash fires at Priest River, Idaho in 1954. The water removed is replaced by air drawn into a mylar sample bag sealed into the container. Figure 21 shows a cutaway view of the entire system.

The mylar sample bag (A) is constructed with an intake tube (B) in one corner. The intake tube is inserted into a one-hole rubber stopper (C) which can be sealed into the spout of a 2-1/2 gallon plastic jerry-jug (D). Prior to sampling, this bag is evacuated and then sealed with a small stopper (E) in the end of the intake tube. The jug is filled with water by removing stopper (C). When starting the sampler, stopper (C) is tightly inserted into the spout of the jug and the siphoning started through siphon tube (F) and head tube (G).

The flow rate of water out of the jug determines the sample flow rate into the bag, and is regulated by the head tube (G) and capillary restriction (H). This combination provides a great deal of flexibility in choosing flow rates while maintaining a reasonably constant flow rate during the sample period. Our work required three different flow rates. Capillary tubing of two different bore sizes, 0.6 mm circular and 0.6x 0.8 mm elliptical, gave flow rates of 63 $\pm$ 2 ml/min and 100 $\pm$ 6 ml/min respectively, when inserted in the downstream end of a 10-foot headtube of 5/16-inch o.d. tygon tubing. With no restriction in the tube, we obtained a flow rate of about one liter per minute. For this particular experiment constant flow was not critical, and no range of variation was determined.

Two types of material were used for sample bag construction; two-ply, 5-mil mylar film (Schjeldahl GT-21); and Scotchpak type 221 polyester/

polyethylene.* We found that bag construction was faster with the Scotchpak material and that fewer problems with leaking seams developed after repeated use. However, both materials were quite satisfactory for maintaining known concentrations of CO and CO_2 for periods of up to 48 hours.

The cost of the system depends, of course, on the types and amounts of materials used, and the experience of personnel in constructing sample bags from mylar materials. Costs for materials on our project came to $2.97 per sampler for 100 samplers. Each sampler required an average of thirty minutes construction time by technicians with no previous experience in working with mylar films. This system allowed us to obtain data from several times the number of points we could have reached with a portable generator, and at a substantially lower cost.

Part of our project was the investigation of pollutant distribution in the vicinity of a 20-acre logging slash fire. Thirty samplers were suspended in a rough grid from tree branches on the downwind side of the fire (sample points are represented by solid dots in figures 11 - 13). These samplers were changed at two-hour intervals, beginning one-half hour prior to ignition of the fire. Two crews of two men each were able to change the thirty samplers in fifteen minutes.

Figure 5 shows the analytical train which we used in our work. CO and CO_2 concentrations from each bag were measured simultaneously by operating Beckman 215 and 315 i.r. analyzers in series. CO_2 concentrations in some cases were too high to measure directly, and in these cases the CO_2 concentrations were measured with a dilution system consisting of a chamber made from a 3-inch length of 2-inch diameter plexiglas. The distribution of CO and CO_2 during three 2-hour periods of this fire are shown as isopleths on the sample grid in figures 11 - 13.

Although the analyzed gases could have been returned to the samplers or stored in another bag or vessel, we chose to vent the outlet of the last analyzer and waste that part of the sampler. We seldom used over half the total available sample material, and the remaining material was sufficient for analysis by I.R. spectrophotometry and gc-mass spectrometry. In addition to the material in the samplers, we collected sufficient material on charcoal for positive identification of gaseous hydrocarbons.

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* We thank Mr. Frank Norris of Lake Oswego, Oregon, and the 3-M Company for generously donating the Scotchpak material which was used in this project.

The analysis of the material from the charcoal filter was used as a check in identifying the hydrocarbons recovered from the material remaining in the samplers. Concentrations of hydrocarbon gases in the samplers ranged from 1 ppb to a high of about 1 ppm.

While this sampler was well suited for analytical procedures such as those we employed, it would not seem appropriate for filtration or bubbler applications.

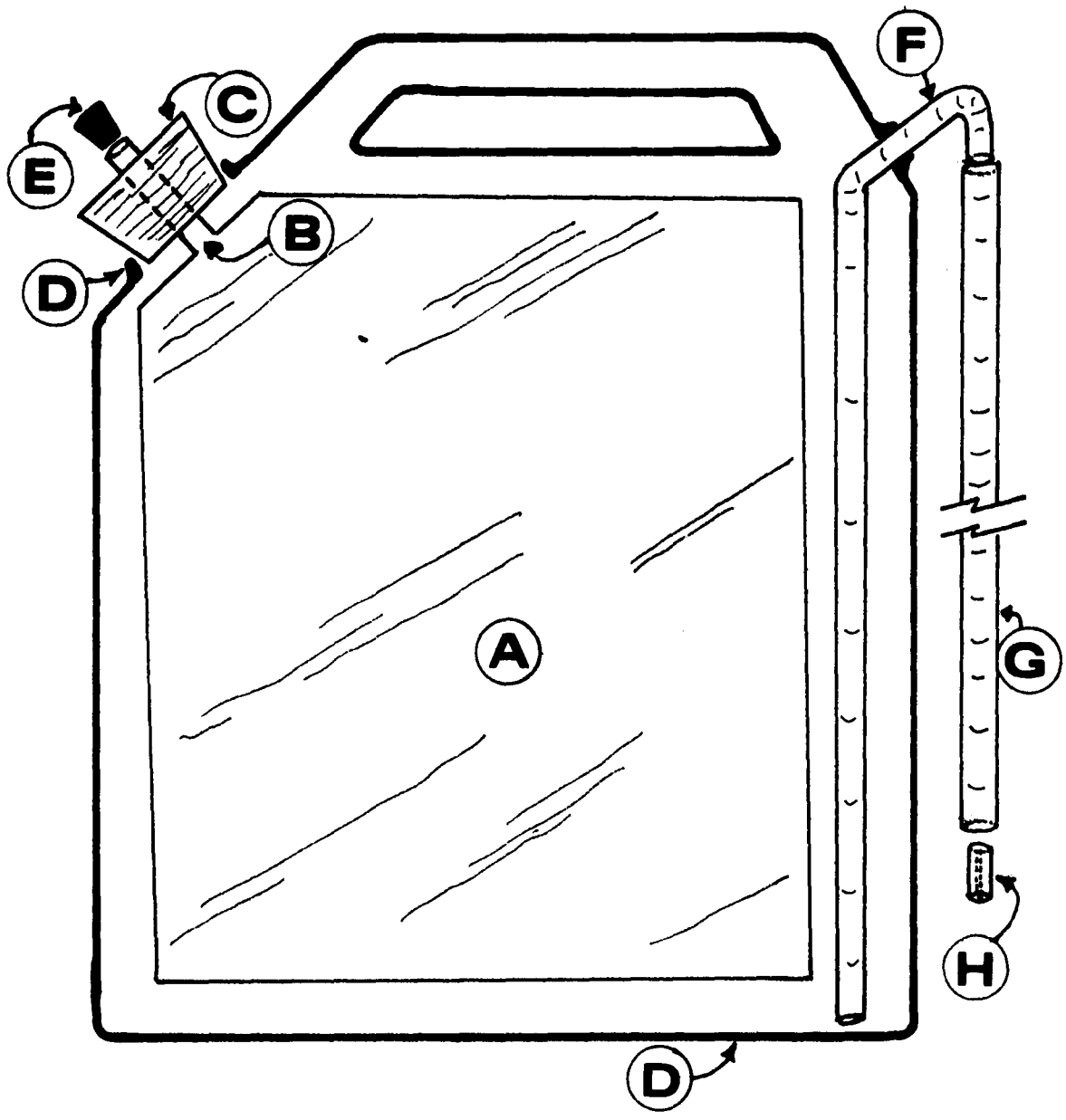

Figure 21 Portable Water-powered Air Sampler.